TRIANGULAR RIBBONS FOR IMPROVED MODULE EFFICIENCY

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ABSTRACT: Different approaches like round wire interconnectors, shingled or back-contact cells have been presented in the past to improve the cell-to-module efficiency ratio by reducing the shading losses of interconnector ribbons.
We present a new cell interconnector design based on a triangular cross section to further improve modules based on interconnector ribbons. We analyze the optical behavior of the concept and compare it with rectangular ribbons and round wire interconnectors. An evaluation of the new concept using optical ray tracing is performed. Results show an advantage in optical performance of 2.35% of the new concept compared to standard interconnector ribbons under perpendicular irradiation as well as 1.94% compared to round wires. An analysis using irradiation data (DNI) shows a superior optical performance of the TriCon-Concept. We find that in an elevation tracked module using TriCon 2.32% more light reaches the cell surface over the year compared to rectangular interconnectors (5BB) and 2.02% compared to round wires.
Keywords: Module, Module Manufacturing, Optical Losses, Performance, PV Materials, Ray Tracing, Ribbons

1 INTRODUCTION

The industrial standard for the electrical interconnection of solar cells are rectangular interconnection ribbons. They are featuring the inherent disadvantage of a flat topside that reflects incident light out of the module which is then lost for power generation. Other concepts have been presented in the past to improve cell interconnection, for instance round wires or light harvesting connectors that have been proven to reflect more light onto the cell and show higher optical efficiencies [1-8].

Solar cells currently shift from three to four or even five busbars [9]. Increasing the number of busbars results in improvements of the electrical efficiency and a cost reduction of solar cells [10, 11]. New approaches like round wires are to be expected to increase the number of busbars and interconnectors even further to up to 15 per cell [5].

In order to improve the concept of round wires we present and evaluate an interconnector design that is based on a triangular shape (“TriCon”) and that can be used on solar cells suitable for round wires like the Multi-Busbar Connectors (MBC) by SCHMID or the Smart-Wire Interconnection by Meyer-Burger [12]. The idea of the TriCon-Concept is to optimize the light harvesting.

We perform a ray tracing simulation to compare the optical properties of rectangular interconnectors, round wires and the triangular connector (“TriCon”). Additionally a combination of the results of the ray tracing-analysis with irradiation data of Freiburg, Germany is performed to estimate gains for a solar module using the different interconnector designs.

2 CONCEPT PRESENTATION

The interconnector as displayed in figure 1 bases on a triangular shape and features a solder coating. It has an edge length of around 400 µm. The coating thickness is identical to standard interconnectors. The corners of the triangle are rounded due to processing limitations and have a radius of around 40 µm.

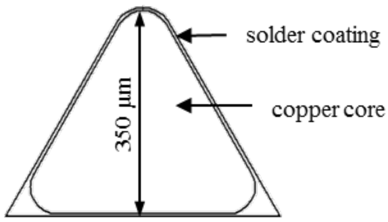

Figure 1: cross section of a soldered triangular interconnector

The dimensions of the triangle are chosen to result in an equivalent total cross section per cell. This leads to similar electrical losses compared to a round wire approach. The triangular wire can be coated with standard coating materials like SnPbAg or SnAg and is therefore compatible with industrial solar cells. The width of TriCon is chosen to be compatible to solar cells suitable for round wires.

Table I: comparison of cross sections of different interconnector technologies

	3BB	5BB	MBC15	TriCon
Number of ribbons per cell	3	5	15	15
Height of ribbon [mm]	0.20	0.20	0.35	0.35
Width of ribbon [mm]	1.50	1.00	0.35	0.40
Cross section per ribbon [mm²]	0.300	0.200	0.071	0.069
Cross section per cell [mm²]	0.900	1.000	1.060	1.039

The triangle is isosceles with internal angles of 60°. Irradiant light is reflected and reduces the cell to module losses by improving the optical performance of the module.

3 SIMULATION

2.1 Optical Analysis of Interconnector Concepts

As shown in Figures 2, 3 and 4 five different cases of reflection can be identified among the different interconnector designs:

1: Light irradiated perpendicular to the cell that is reflected out of the module.
2: Light irradiated under a non-perpendicular angle that is reflected out of the module.
3: Light irradiated under a non-perpendicular angle at the side of the interconnector / the solder that is reflected onto the cell.
4: Light irradiated perpendicular to the cell that is reflected onto the cell.
5: Light irradiated under a non-perpendicular angle that is reflected onto the cell.

Additionally a sixth important case is observed where light is reflected on the front cover after reflection on the interconnectors. All described cases are only valid for angles that are perpendicular regarding the axis of the interconnector ribbons.

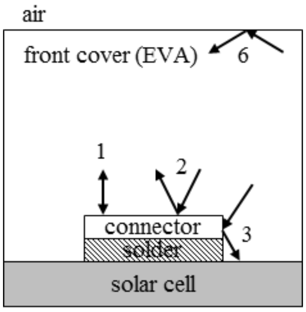

Figure 2: incident and reflected light for rectangular interconnectors

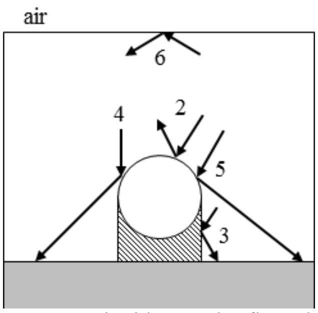

Figure 3: incident and reflected light for round wires

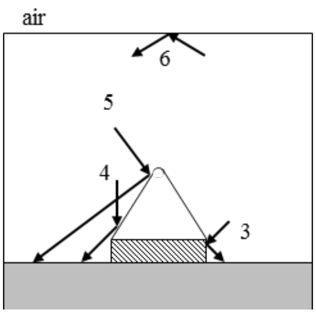

Figure 4: incident and reflected light for triangular interconnectors

The rectangular interconnector reflects a significant amount of light away from the solar cell (see Figure 2, No 1 and 2) which is lost for power generation. This loss may be reduced by additional reflections that can occur on the front interface of the module (Figure 2, No 6). Due to reflections on the side of the interconnector (Figure 2, No 3) additional gains may occur. Since perfect reflection on the side does not occur, the additional shading of the non-illuminated side of the interconnector compensates this gain. Diffuse reflections reduce the optical width of the interconnector and improve its optical performance [2, 13, 14].

For the round wire interconnector and TriCon reflections of type 1 are virtually non-existent while reflections to the solar cell or the front interface of the module increase.

Based on the geometry of TriCon reflections within the module can be divided into two groups for different angles which are illustrated in Figure 5.

The first type (a) describes light irradiated between ±30° and reflections on both sides of the triangle onto the cell. The second case occurs for light irradiated with angles above 30°. Here light is shading part of the cell (b) or is reflected back to the front surface (c) to be then reflected again (d).

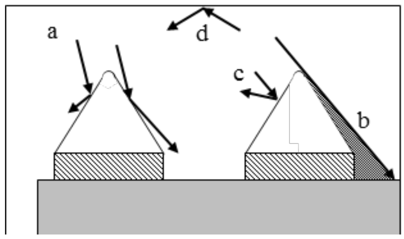

Figure 5: Reflections under different angles at a triangular connector

While reflections of type (e) are virtually non-existent for round wires a shading (Figure 6, b) of direct light occurs for every non-perpendicular incidence angle (Figure 6, d). Reflections onto the cell (b) and towards the front cover (c) are unchanged. Additional reflections on the front cover (d) might occur.

Since angles larger than approx. 42° are not possible within a module due to Snell's law of refraction, shading (b) and reflections of type (c) are not significant for TriCon.

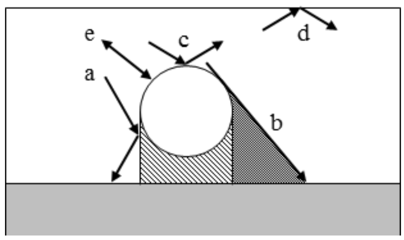

Figure 6: Reflections under different angles at a round wire connector

2.2 Ray Tracing Setup

We perform a ray tracing analysis using the finite elements method (FEM) to prove the optical advantages of the triangular interconnector. A solar cell (156 x 156 mm²) is irradiated under different angles and the reflection on interconnector ribbons is calculated.

A whole cell with the correspondent number of interconnectors is simulated. The model is a 2D model using 100.000 rays. A sweep of the incident angle from 0° to 80° is performed. The rays have a wavelength of 1000 nm. The cell is embedded in EVA that also provides the front interface of the simulation setup (Figure 2). The solar cell is modelled as a perfect absorber to independently evaluate effects caused by the interconnection. A simulation of the cell without any interconnectors is used as a reference value.

We set the reflectivity of the interconnector to be 0.80 and the reflections to be 80 % specular and 20 % diffuse. Multiple reflections on the interconnector and the front cover are computed. The thickness of the solder is set to 20 µm. All remaining geometries are shown in Table 1.

2.2 Ray Tracing Results

Figure 7 shows the results for angles between 0° (perpendicular irradiance on the solar cell) and 80°.

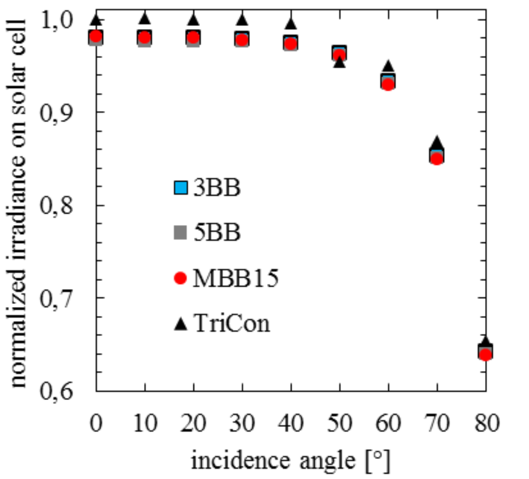

Figure 7: Optical performance of different interconnector technologies at different incidence angles, normalized irradiance on a solar cell

Simulation shows an advantage of the triangular ribbons for most angles of irradiance. Gains above 30° result from secondary reflections on the front glass. Round wires also gain from multiple reflections and increased reflections towards the cell (see Figures 3 and 4). The dip at 50° results from an optical interaction between TriCon interconnectors and the front cover interface. Nonetheless the optical properties of the TriCon-concept additionally increase the performance of the module.

The TriCon concepts shows approximately 2.35% higher efficiency than the rectangular interconnectors (5BB) perpendicular irradiation and 1.94% compared to round wires. The differences between three and five busbars result from the larger footprint of the five busbars.

2.2 Yield Simulation

Since irradiation on a solar module is incident under varying angles and radiance is not evenly distributed within these angles a calculation using irradiation data is performed [6]. We use data of Meteonorm 7 for a module mounted in Freiburg, Germany. The module is facing south and is mounted as shown in Figure 8. We calculated the incident angles for a fixed module (45°), an elevation (around horizontal axis) tracked and an azimuth (around vertical axis) tracked module. The interconnector ribbons run vertically within the module.

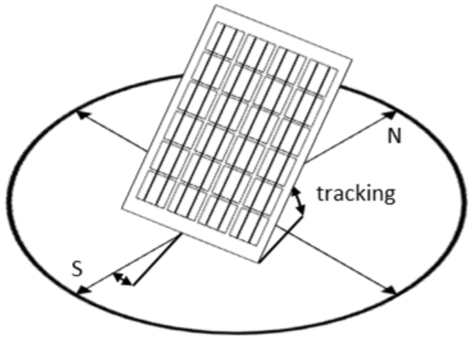

Figure 8: assumed mounting of the module with different types of tracking

Figure 9 shows the yearly direct irradiation incident within a certain range of angles. It is obvious that tracking results in lower incidence angles and therefore in lower optical losses.

To eliminate the influence of the elevation of the sun for the calculation, the module is assumed to be tracked vertically. Only changes of the azimuth are used for the yield estimation. This results in a sun path perpendicular to the axis of the interconnector ribbons and therefore in an optical behavior as shown in figures 1 to 6.

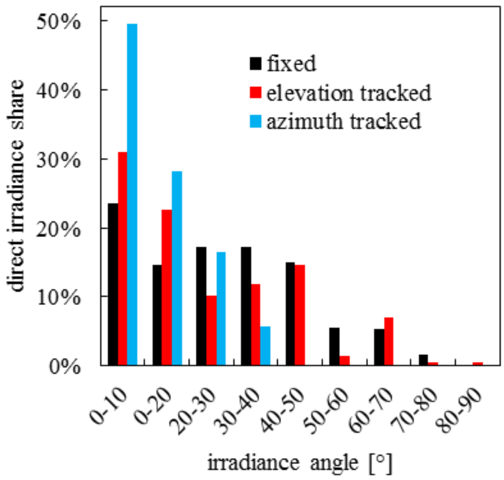

Figure 9: angular direct irradiation distribution on module plane for fixed and tracked modules in Freiburg, Germany

By combining data of Figures 7 and 9 a comparison of the different interconnector technologies is possible. It clearly indicates an advantage of the triangular interconnector design compared to other designs.

We only consider direct normal irradiance (DNI). This simplification might reduce the advantage of TriCon although Figure 7 shows an advantage of TriCon for most angles.

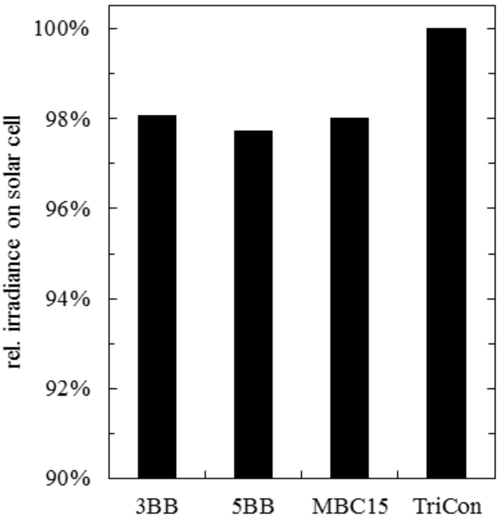

Figure 10: Optical performance of different interconnector technologies for a vertically tracked module mounted in Freiburg, facing south

Figure 10 shows a 2.02 $\%_{rel}$ higher optical efficiency of the TriCon-concept compared to the round wire approach after considering annual environmental irradiation and angular power distribution. Compared to five rectangular connectors the triangular connector gains 2.32$\%_{rel}$. Again the difference between three and five busbars only results from the increased footprint of the five busbars. Electrical advantages of the higher number of busbars are not considered for all concepts.

The optical efficiency directly relates to the power generation of the solar cell and therefore a gain can be achieved by using TriCon interconnectors.

3 SUMMARY

A new interconnector design is presented based on a triangular cross section. An analysis of the optical behavior of different types of cell interconnectors is conducted and a more complex behavior of round wires and TriCon can be observed.

A ray tracing simulation is performed to analyze the angular-dependent reflections of three interconnector concepts. Results show a superior optical performance of the TriCon ribbons. For irradiation perpendicular to the module TriCon shows a 2.35% higher optical performance than five busbars and 1.94% compared to round wires.

We conduct a yield estimation for a module using different interconnector designs using irradiation data. The yield analysis uses direct normal irradiance for Freiburg, Germany and an elevation tracked module. Results show that 2.32% more light is reaching the solar cell (optical performance) in a module using the triangular connector compared to a module with five busbar, rectangular ribbon interconnection and 2.02% more compared to round wires.

4 REFERENCES

[1] Zarmai, T., et al, “A review of interconnection technologies for improved crystalline silicon solar cell photovoltaic module assembly, Applied Energy, Volume 154, pp. 173-182

[2] Wirth, H., et al, Advances in Photovoltaics, Vol. 2, pp. 160-193, Burlington: Academic Press, 2013

[3] Eitner, U., et al, “Progress in HIP-MWT module technology“, MWT-Workshop 2013, Freiburg (Germany), 2013

[4] Eitner, U., et al, „Interconnector-based module technology for thin MWT cells“ 27th PVSEC, Frankfurt, 2012

[5] Walter, J., et al, “Multi-wire interconnection of busbar-free solar cells”, SiliconPV 2014, ‘s-Hertogenbosch, 2014

[6] Braun, S., et al, “Solar cell improvement by using a multi busbar design as front electrode”, SiliconPV 2012, Leuven, 2012

[7] Ebert, M., et al, “The Impact of Angular Dependant Loss Measurement on PV Module Energy Yield Prediction”, 29th PVSEC, Amsterdam, 2014

[8] Schneider, J., et al, “Combined effect of light harvesting strings, anti-reflective coating, thin glass, and high ultraviolet transmission encapsulant to reduce optical losses in solar modules”, Progress in Photovoltaics, Vol. 22, pp. 830-837, 2014

[9] International Technology Roadmap for Photovoltaic, ITRPV Seventh Edition 2016, VDMA

[10] Braun, S., et al, “The multi-busbar design:an overview”, 4th Workshop on Metallization for Crystalline Silicon Solar Cells, Erschienen in: Energy Procedia ; 43 (2013) S. 86-92, 2013

[11] Hendrichs, M., et al, “Advanced Metallization Concepts for p-type Silicon Metal-Wrap-Through (MWT) Solar Cells”, Energy Technology, Vol. 2, DOI: 10.1002/ente.201300094, 2014

[12] Faes, A., et al, "SmartWire solar cell interconnection technology." 29th PVSEC, Amsterdam, 2014

[13] Woehl, R., et al, “Analysis of the Optical Properties of Screen-Printed and Aerosol-Printed and Plated Fingers of Silicon Solar Cells”, Advances in OptoElectronics, Volume 2008 (2008), Article ID 759340, 2008

[14] Stuckings, M.F., et al, “A study of shading and resistive loss from the fingers of encapsulated solar cells”, Solar Energy Materials and Solar Cells, Volume 59, Issue 3, October 1999, Pages 233–242, 1999