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MOSAIC MODULE CONCEPT FOR COST-EFFICIENT AND AESTHETIC BIPV MODULES

Max Mittag, Matthieu Ebert, Helen Rose Wilson, Tobias Fellmeth
Fraunhofer Institute for Solar Energy Systems ISE, Heidenhofstr. 2, 79110 Freiburg, Germany
max.mittag@ise.fraunhofer.de

ABSTRACT: We present a module concept based on metal-wrap-through solar cells and conductive copper backsheets that offers a high degree of aesthetic freedom and allows individual designs. Our metal-wrap-through cell design features sub-cells that allow splitting and individual cell sizes enabling a flexible module design. We show results from sample manufacturing and façade mock-up implementation. The manufacturing is performed using automated equipment and low-temperature solder pastes. The process step of “tabbing/stringing” can be omitted compared to conventional PV module manufacturing. We perform IV measurements and a cell-to-module loss analysis. Results show that, considering the aperture area of the cells, competitive cell-to-module power ratios (~95%) are achieved. We estimate the mosaic module costs to be between 58 and 70 €/m² (depending on specific design) compared to 45 €/m² for common industrial, utility scale solar modules.

Keywords: photovoltaic module, Building Integrated PV, BIPV, MWT, electrically conductive backsheets, low temperature solder paste, flexible module design

1 INTRODUCTION

The success of Building-Integrated Photovoltaics (BIPV) strongly depends on the appearance of modules in façades and building envelopes. In addition to aesthetic demands, a high module efficiency and a cost-effective production are necessary [1–3]. These requirements usually represent a target conflict [4, 5].

We develop a module concept which offers design flexibility, high efficiency potentials as well as low production costs [6].

The mosaic module concept is based on metal-wrap-through (AP-MWT) cells [7]. The MWT solar cells are manufactured from common 6” wafers but are designed to be separated into smaller pieces (Figure 1).

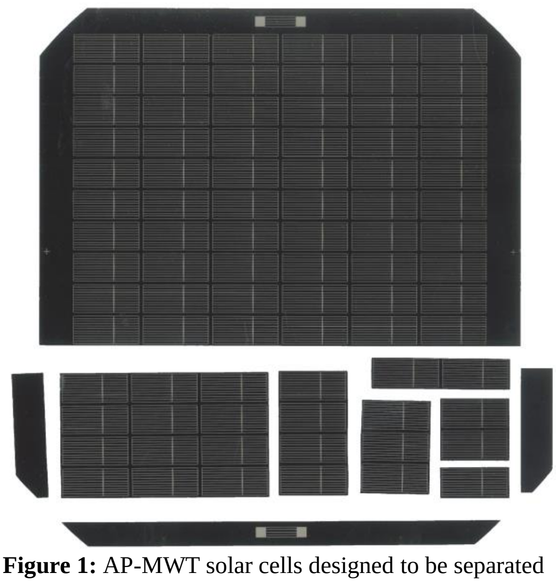

Figure 1: AP-MWT solar cells designed to be separated

The module includes a structured, electrically conductive backsheet that allows flexible positioning of solar cells. The smaller cells together with the variable configuration and different color of the backsheet result in a highly customizable module design (Figure 2).

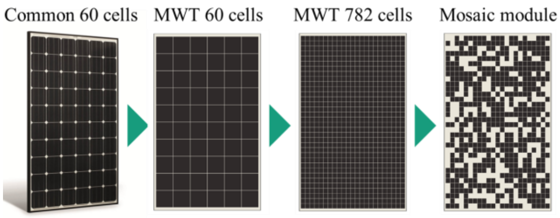

Figure 2: Design flexibility of the mosaic module concept

We apply a cell interconnection based on low-temperature solder paste and a stencil printing process. The suitability for BIPV applications is demonstrated with flexible designs. We present several prototypes of different appearance. A Cell-to-module (CTM) analysis and IV measurements as well as cost estimations are performed.

2 THE ALL-PURPOSE-CELL CONCEPT

The mosaic module concept is based on metal wrap-through (MWT) solar cells [7–9]. These cells are back-contact solar cells, where the electrical front contact is connected to the rear side through laser-drilled holes. Electrical cell interconnection is located on the cell rear surface reducing the shading by interconnector ribbons and thus allowing higher cell power. The visual homogeneity of the solar cell is improved, which is desirable for BIPV modules. The 6” wafers are designed to allow separation into solar cells of different sizes (Figure 1).

The cell concept is named “all-purpose MWT” (AP-MWT) to reflect flexibility. The variability in cell sizes is achieved by adapting the front and back metallization to smaller cell elements providing contact pads for each of those elements (Figure 3). A full-size AP-MWT cell can be separated into sub-cells with a minimal size of 22.5 x 10 mm².

Figure 3: Front and rear view of an all-purpose MWT solar cell for low-concentrating PV applications

The AP-MWT cells can be optimized for variety of different operation conditions such as for facade applications with reduced irradiance due to non-optimal module orientation, for low-concentration PV modules (LCPV, Figure 4) [9] with increased irradiance as well as for device integration [8].

Figure 4: LCPV receiver with AP-MWT solar cells

To determine the optimal cell design for the application in the mosaic module concept, we perform a simulation of the cell efficiency as a function of the irradiance and the number of metal fingers on the front side using Fraunhofer ISE GridMaster [9–11].

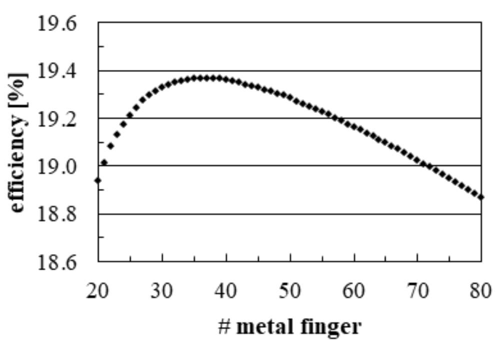

Figure 5: AP-MWT cell efficiency as a function of the number of metal fingers at standard testing conditions calculated using the software GridMaster

A cell design has been specified for mosaic module prototyping with a size of 69.5 x 67 mm² featuring 12 pairs of n and p contacts for soldering (Figure 6).

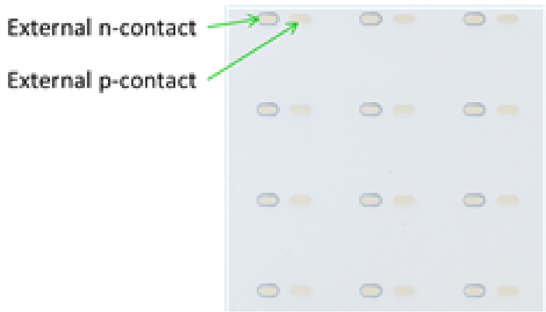

Figure 6: Rear view of an all-purpose MWT solar cell segment with 12 external n and p contacts

The solar cells for this study were manufactured at Fraunhofer ISE PV-TEC and achieve an average efficiency of 19.4% (cell manufacturing in 2015).

3 THE MOSAIC MODULE CONCEPT AND MANUFACTURING

The mosaic module is based on the idea that smaller solar cells provide a higher degree of design freedom for BIPV applications (Figure 2) and that individually structured electrically conductive backsheets (ECB) allow flexibility in solar cell and bypass diode positioning (Figure 7, Figure 8) [12].

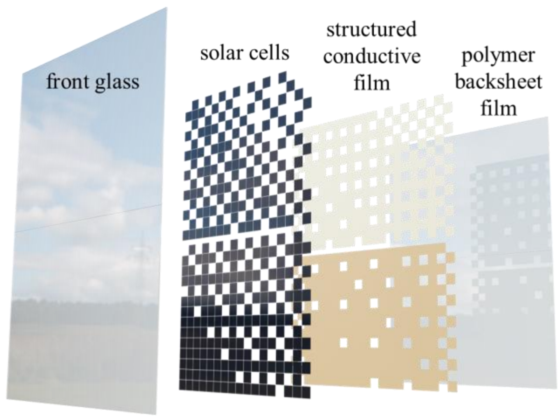

Figure 7: Mosaic module configuration

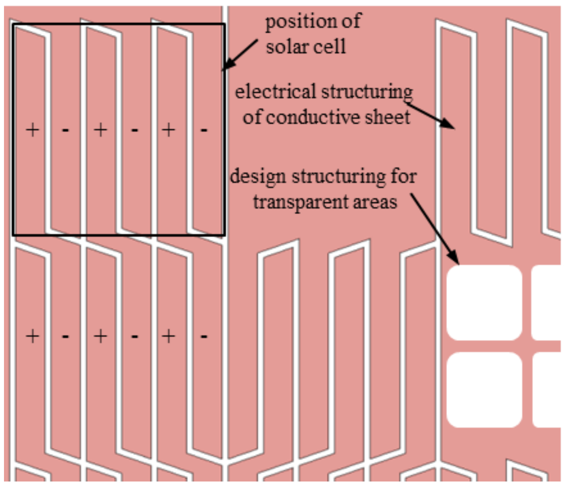

Figure 8: Electrically conductive copper sheet design for flexible cell positioning (example)

The structure of the backsheet provides separate positive and negative electrical contacts. Different structuring of the electrically conductive copper sheet and additional interlayers allow a semi-transparent or colored module appearance (Figure 9, Figure 10).

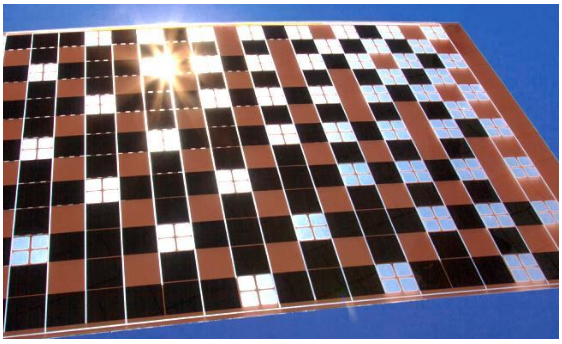

Figure 9: Partly transparent mosaic module prototype

Figure 10: Façade mock-up of mosaic PV modules with different designs and solar cell coverage; top module: 119 AP-MWT cells (38.9% of area photovoltaically active); bottom module: 167 AP-MWT cells (55.0% of area photovoltaically active).

We manufactured modules of different designs with a size of 1460 x 975 mm² (1.42 m²). The first design included 119 AP-MWT cells and the electrically conductive backsheet was combined with a transparent polymer film to allow translucent module areas (Figure 9). The second design includes 167 AP-MWT solar cells and a white polymer film resulting in a totally opaque module (Figure 10). Both modules use 3.9 mm low-iron glass without anti-reflective coating (ARC) and AP-MWT cells with an area of 69 x 67.5 mm² and an average efficiency of 19.4%. Due to the different number of cells, each module configuration has different string lengths. The first design has four strings (34, 31, 27 and 27 solar cells) were the first and last two are connected in parallel and where these parallel blocks are then connected in series. The second design features four strings (47, 42, 37 and 41 cells) all connected in parallel. A series string interconnection and other electrical module topologies are possible but have not been implemented.

While the MWT cells and the ECB would also allow smaller cell spacing, we used a cell distance of 2 mm. The module designs have a relative active area of 38.9% and 55.0%, respectively. Commercially available SnBi58 low-temperature solder paste (LTSP) with 10% flux and EVA encapsulant were used for soldering and lamination, respectively. Cell separation and module manufacturing were performed at Fraunhofer ISE Module-TEC using automated equipment (Figure 11).

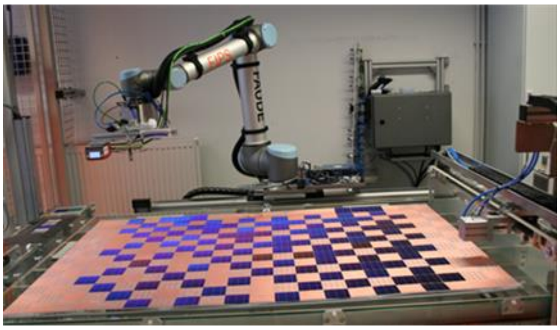

Figure 11: Automated mosaic module production at Fraunhofer ISE Module-TEC

The paste is applied onto the back of the cells using stencil printing before lay-up. The cells with paste are then placed on the electrically conductive backsheet using a six-axis robot system and visual control to increase accuracy in positioning (Figure 12). The electrical cell interconnection forms during lamination using a typical lamination process profile, allowing fast and economic module production. We perform electroluminescence and x-ray inspection of the modules to verify the electrical interconnection between cells and the copper sheet (Figure 12, Figure 13).

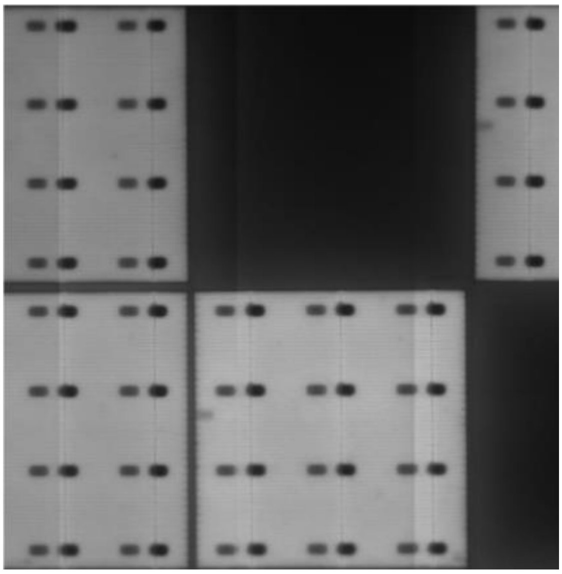

Figure 12: Electroluminescence image of a manufactured mosaic module

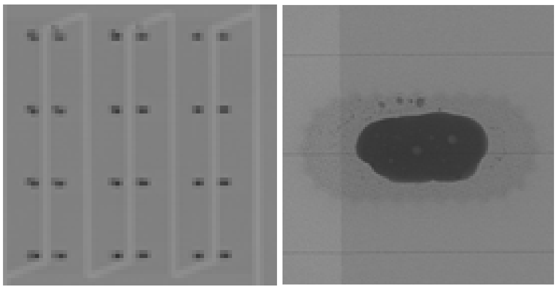

Figure 13: X-ray image of a cell (left) and a selected solder pad (right) showing low-temperature solder paste interconnection

4 POWER MEASUREMENT AND CELL-TO-MODULE (CTM) ANALYSIS

We measure the power of both modules at Fraunhofer ISE CalLab Modules and find the first design to have 102 Wp and the second to have 112 Wp. Due to the uneven string lengths, deviations between the electrical properties of the solar cells and the module topology (mixture of series and parallel string interconnection), significant electrical mismatch losses occur. These losses could not be avoided in the manufactured modules due to the design specifications of the façade mock-up (Figure 10). Specifications requested certain cell patterns, edge margins and mounting tools that made a disadvantageous string interconnection necessary. The focus of this study is on the proof of concept and to demonstrate the possibilities regarding module design and visual appearance. No attention was paid on avoiding mismatch losses but general design rules have been established that allow the reduction of such losses for future designs.

Using only the aperture area of the cells (cell area + 1 mm spacing), we calculate efficiencies of 18.2% for design-optimized versions of the first and 14.4% for the second module. We use the aperture area since the module area would be misleading due to the large inactive area share which is a desired part of the BIPV system design. CTM ratios are displayed in Table I.

Table I: module measurement results and CTM ratios

Module	1	2
Cells	119	167
Total cell power	107.2 Wp	150.5 Wp
Module power	101.7 Wp	112.3 Wp
Module efficiency	7.1%	7.9%
CTM_{power} (aperture area)	94.8%	74.6%
$CTM_{efficiency}$ (module area)	36.6%	40.7%
$CTM_{efficiency}$ (aperture area)	93.8%	74.2%
Active module area share	38.9%	55.0%

CTM analysis shows high losses in nominal efficiency due to the low share of active cell area within the module. CTM_{power} for module 1 is lower than for commercially available, common modules due to lower backsheet gains (copper instead of white backsheet), the lack of an AR coating of the front glass and electrical mismatch losses [13]. Nonetheless, the analysis shows that the mosaic module is capable of effectively generating power and that efficiency losses occur mainly due to aesthetic demands.

5 COST ESTIMATION

We estimate costs of the mosaic modules using the “SCost” model developed at Fraunhofer ISE [14]. The model is based on SEMI E35 and E10 standards for the calculation of costs of ownership. We assume a small industrial production line with 1835 hours manufacturing per year (90% factory uptime for a single working shift, 5 days per week, 51 weeks per year) and 53.5 modules per hour. The total output is approx. 110.000 modules per year.

Table II shows relevant module components and their prices as they were used in the cost estimation. The price assumptions are based on a literature review and market survey and include a surcharge for small order quantities. Costs for engineering and BIPV project management are not included.

Table II: Material prices used for cost estimation

AP-MWT solar cells	0.25 €/Wp
EVA encapsulant	1.00 €/m²
Glass	4.00 €/m²
electrically conductive backsheet	10.00 €/m²
low-temperature solder paste	150 €/kg
junction box	4.00 €/pcs

For cost calculation we assume a module design without mismatch losses. We calculate the module costs for design-optimized versions of design 1 to be 82.50 € (81 €ct/Wp, 58.1 €/m²) and of module 2 to be 98.92 € (66 €ct/Wp, 69.7 €/m²). We find the costs higher compared to common industrial, utility scale solar modules (300 Wp, 0.25 €ct/Wp, 1.65 m²) which range at around 45 €/m². The costs of the mosaic module are higher due to the necessary copper sheet, the price of the low-temperature solder paste and the low area coverage of the solar cells (Figure 14). The share of the costs of the solar cells is lower than for conventional modules [13, 15]. Comparing our results to other custom-designed BIPV modules, we find the mosaic module to be competitive compared to other BIPV products [16, 17]. Costs for engineering, design or costs related to specific BIPV projects costs have not been considered.

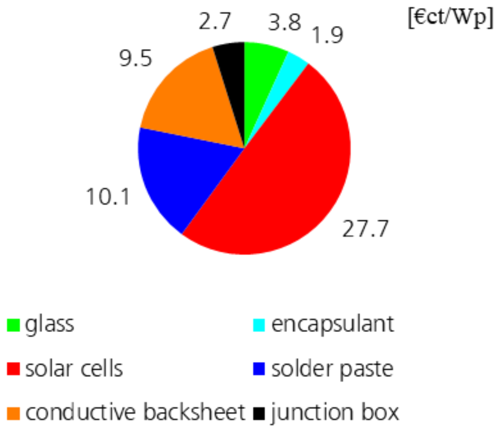

Figure 14: Cost of Ownership structure of the mosaic module design 2

6 SUMMARY

We present a module concept for building integration based on MWT solar cells and conductive backsheets that offers a high degree of aesthetic freedom and allows individual module designs. We show prototypes with different visual appearance and façade mock-up implementation. The manufacturing is performed using automated equipment and low-temperature solder pastes, avoiding the process step "tabbing/stringing" compared to conventional PV modules.

We perform a cell-to-module loss analysis. The results show that based on aperture area, competitive cell-to-module power ratios (~95%) are achieved.

We perform a cost analysis and find the mosaic module costs to be between 57 and 69 €/m² (depending on specific design), which is comparable or even lower than other published BIPV products.

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