Progress in PHOTOVOLTAICS

PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS
Prog. Photovolt: Res. Appl. (2016)
Published online in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/pip.2844

EU PVSEC PAPER

GaInP/AlGaAs metal-wrap-through tandem concentrator solar cells

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ABSTRACT

III–V multi-junction solar cells are promising devices for photovoltaic applications under very high concentration levels of sunlight. Shadowing losses of the front side metallisation and ohmic resistance losses in the metal grid limit the practical cell size typically to around 1 cm^2 at 1000 suns. The use of a full back-contact architecture, similar to the metal-wrap-through (MWT) technology known in silicon photovoltaics, can help to overcome this limitation. Furthermore, positioning both the positive and negative contact pads on the rear side of concentrator solar cells opens the possibility for efficient packaging solutions and the realisation of dense array receivers with low metal shadowing. The MWT technology addresses conventional concentrating photovoltaics as well as combined conventional concentrating photovoltaic-thermal applications and offers specific advantages for large-area devices at high intensities. This work presents the first experimental results for MWT architectures applied to III–V tandem solar cells and discusses specific challenges. An efficiency of 28.3% at 176 suns and 27.2% at 800 suns has been measured for the best MWT $Ga_{0.51}In_{0.49}P/Al_{0.03}Ga_{0.97}As$ tandem solar cells. Copyright © 2016 John Wiley & Sons, Ltd.

KEYWORDS
back contact; concentrator cells; gallium arsenide-based cells; high-efficiency; III–V semiconductors; multi-junction solar cell

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Received 28 April 2016; Revised 11 October 2016; Accepted 12 October 2016

1. INTRODUCTION

The highest light-to-electricity conversion efficiencies are achieved with photovoltaic devices made of III–V semiconductor materials. For this reason, they are the candidate of choice for many high-performance applications such as satellite power generation, high-concentration photovoltaics (PV) and optical power transmission [1,2]. Four-junction solar cells with a record efficiency of 46.1% (at 312xAM1.5d) have been demonstrated [3] by using wafer bonding, and several other device architectures have also been suggested [4–6], including inverted four-junction solar cells which have reached efficiencies up to 45.6% (at 690xAM1.5d) [7]. Typical concentrator solar cell devices in high-concentration PV modules have dimensions of 1 mm^2 up to 1 cm^2 and operate at concentration levels between 200 and 1500 suns. Even larger area devices are used in parabolic dish mirror systems with dense array receivers [8,9]. Such receivers may cover an area of 100 cm^2 up to 1 m^2 and operate at intensities of 1000 suns or higher. Ohmic resistance losses scale with the square of the current and therefore become a major concern for large area, high-concentration devices. These losses must be balanced carefully with the amount of metal on the front side of the solar cell, which may lead to significant shading. Monolithic series connection of small solar cell segments has been proposed to minimise shading and resistance losses for large-area devices at high concentration levels [10,11]. Such approaches limit the current through series connection and higher voltage but require trenches for the inter-connection which lead again to additional inactive area.

The challenge of high currents and metal shading in silicon PV has led to the development of metal-wrap-though (MWT) technologies in which the emitter and base contacts are both realised on the rear side of the device. Insulated holes are filled with metal to transport the electric current from the front to the back side where both contacts are isolated and collected in an interdigitated metal grid [12,13]. This technology has led to Si solar cells with an efficiency up to 21.0% (AM1.5 g) [14]. But this technology has never been applied to III-V multi-junction solar cells. A conceptual study was presented by Zhao *et al*. [15] in 2012, but the realisation of such devices is complex. In this paper, we discuss how the MWT technology was adapted to realise the first functional devices in an inverted $Ga_{0.51}In_{0.49}P/Al_{0.03}Ga_{0.97}As$ tandem solar cell. We further show the influence of design variables like via pitch and pattern and discuss the influence of local shunts on the characteristics of concentrator solar cells. The MWT technology can be applied to three-junction and four-junction devices in the future to reach higher conversion efficiencies above 40% [7].

2. BENEFITS OF CONCENTRATOR MWT CELLS

The task of optimising the front metal grid for conventional concentrator photovoltaic devices includes finding an optimum between resistance and shading losses. Minimum width and maximum height of metal fingers as well as appropriate shape for sidewall reflection of photons into the solar cell are typical design variables. Such front contact grid optimisation has been performed at Fraunhofer Institute for Solar Energy Systems (ISE) for GaInP/AlGaAs dual-junction solar cell devices by using SPICE network simulation. Detailed descriptions of this modelling method can be found in Ref. [16]. Shading losses by the contact grid metallisation with different geometries optimised for a concentration ratio of 800 suns are presented in Figure 1. The optimal finger geometry depends on the cell size, and shading reaches up to 14% for a $1\times1\text{-cm}^2$ device with a $10\times2.7\text{-µm}$ finger profile. The shading may be reduced to below 10% by lowering the metal finger width and increasing the height. But processing finger geometries with aspect ratios >1 or finger width <4 µm is not practical with photolithography and lift-off.

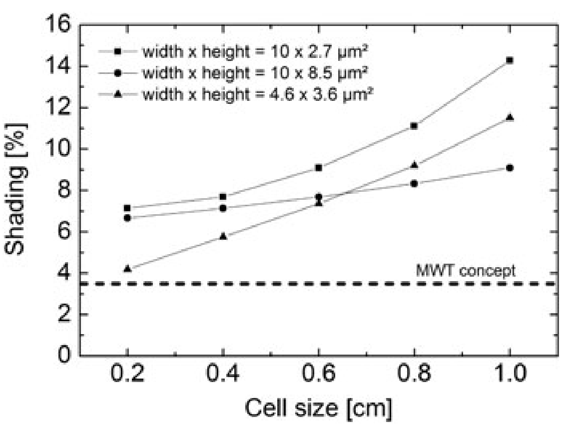

Figure 1. Shading by the front contact grid calculated for a GaInP/GaAs tandem solar cell optimised for 800 sun concentrations of the AM1.5d spectrum and different metal finger geometries.

The MWT technology allows a significant reduction in front metal grid shading by conducting the current of the emitter through insulated via holes to the rear side of the solar cell where large metal areas do not cause additional shading. The possible gains of the MWT concept in III–V multi-junction solar cells are studied in Ref. [17]. The absolute efficiency improvement for a 0.49-cm^2 triple-junction GaInP/GaAs/Ge solar cell at high concentration levels of 500–2000 suns is estimated to be in the range of 1.9–3% compared with a conventional design. Higher gains are possible for larger cells and higher concentration levels. An efficiency improvement of 10% (4% absolute) at 500 suns was calculated in Ref. [15] for InGaP/GaAs/InGaAs inverted metamorphic triple-junction solar cells. Furthermore, a dry etching process for the formation of via holes in inverted metamorphic structures has been successfully demonstrated in Ref. [15].

We conducted a simulation based on the double diode model by using experimental data of GaInP/AlGaAs dual-junction solar cells, assuming a back-contact cell design with a via-hole diameter of 26 µm and a hexagonal via pattern. The shadowing losses of the MWT cell obtained for 800-fold concentration is only 3.5%, as presented by the dotted line in Figure 1, which offers significant advantages in the overall shading of large-area devices.

3. EXPERIMENTAL APPROACH

Inverted dual-junction $Ga_{0.51}In_{0.49}P/Al_{0.03}Ga_{0.97}As$ solar cell structures were grown on GaAs by using an AIX2800G4-TM metal-organic vapour phase epitaxy reactor with an $8\times4''$ configuration. The hydride sources arsine and phosphine were used for the group V growth. Trimethylgallium, trimethylindium and trimethylaluminium were the group III precursors. Doping sources were dimethylzinc, diethyltellurium, ditertiarybutylselenide, silane and carbon tetrabromide. All structures were grown on 4 inch, 450-µm-thick GaAs wafers with an orientation of (100) 6° off towards (111)B. Growth temperatures varied between 530 and 680 °C, and the reactor pressure was between 50 and 100 mbar. V/III ratios of 30–50 for AlGaInAs and 40–150 for AlGaInP have been used. The total thickness of all compound semiconductor layers was 5.1 µm, divided into a 0.9-µm-thick $Ga_{0.5149}In_{0.49}P$ top cell ($E_g = 1.88$ eV) and a 2.8-µm $Al_{0.03}Ga_{0.97}As$ ($E_g = 1.45$ eV) bottom cell. Both solar cells had an n-type emitter layer and a p-type base layer surrounded by higher bandgap barriers made of Al-containing alloys. The two subcells were inter-connected in series by an AlGaAs/GaInP tunnel diode, and the full layer structure was grown on a GaInP release layer which allowed selective removal of the GaAs substrate during processing.

The GaInP top cell was passivated by an n-AlInP window layer followed by a 400-nm n-GaAs cap layer which was highly doped to $>5\times10^{18}\,cm^{-3}$. The same structure is used for tandem solar cells with a conventional front metal grid and allows reaching low contact resistance in the range of $1–6\times10^{6}\,\Omega\,cm^2$. For the MWT solar cells, an ohmic metal was applied to the GaAs cap layer and connected to the rear of the device by insulating vias. The density of these vias was selected for a concentration ratio of 800 suns. Simulation results were used as guiding values for via pitch variations in the range of 50–700 µm on cells with three different via layouts, as can be seen in Figure 2. The metal vias were arranged in a square or hexagonal pattern, and in one configuration, additional metal fingers were added between the vias to facilitate current collection. This configuration is beneficial in cases where the overall resistance is limited by the emitter sheet and consequently lateral transport of electrons to the vias.

The GaInP/AlGaAs solar cell structure was grown in an inverted direction which gives direct access to the back side of the device structure. During processing, an ohmic planar back contact was evaporated first, followed by a non-selective inductively coupled plasma etch of vias with a diameter of 10 µm. The surface of the metal and the vias were conformally coated with insulating Si_3N_4/SiO_2 and TiN as a diffusion barrier before filling the vias with electroplated copper. This resulted in a layer stack of back metal, insulation and front metal. This stack was bonded to a conductive silicon carrier, and the GaAs substrate (used for the growth of the tandem cell and for mechanical stability) was removed to give access to the GaAs cap. After removing the release layer in concentrated HCl and opening the vias from the top, the GaAs cap layer was etched in a solution of citric acid : H_2O_2 : H_2O of approximately 3:1:1, and a two-layer Ta_2O_5/MgF_2 anti-reflection coating was evaporated. Ohmic metal contacts were applied with the geometry shown in Figure 2. Finally, the cell area was defined by non-selective wet chemical etching in a 1:1:5 HBr : H_2O_2 : H_2O solution.

The overall design of the back-contact MWT solar cells is presented in Figure 3. Access to the solar cell back contact was made after mesa etching from the top, whereas the front contact was accessible through the silicon carrier substrate. The different layers and contacts are illustrated in Figure 3, and further details of the processing are published in Ref. [18]. It has to be mentioned that the current cell design has not been realised as a full back-contact device which is subject to future developments. But the current design offers all the benefits of the MWT concept to minimise shading on large-area concentrator solar cells. A substantial number of 4.2×4.2 and $9.5\times9.5\text{-mm}^2$ MWT cells have been processed for testing.

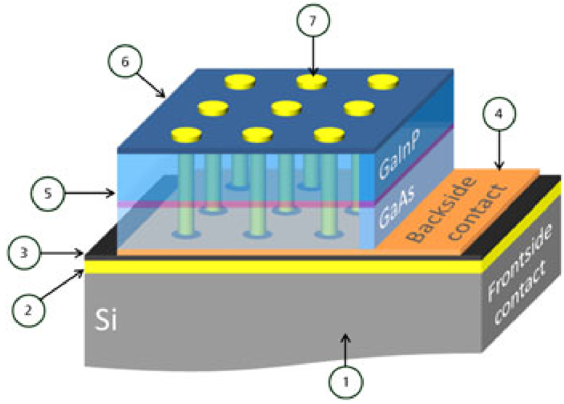

Figure 3. Schematic illustration of the metal-wrap-through (MWT) cell architecture with (1) silicon carrier, (2) electroplated copper, (3) Si3N4/SiO2 insulation (black), (4) back-side contact, (5) GaInP/GaAs tandem solar cell structure, (6) Ta2O5/MgF2 anti-reflective coating and (7) front side contact connected to copper-filled insulated vias.

Figure 4 shows a cross-section of a via hole as the most critical element of the MWT device structure. The via hole is filled with electroplated copper and insulated carefully from the tandem-cell structure and the rear-side contact metallisation. The diameter of the front ohmic metallisation is relatively large (~23 µm) and could be reduced in the future to about 15 µm. The width of the grid lines was 5 µm in the 'square + lines' design.

4. RESULTS AND DISCUSSION

Electrical characterisation of processed devices was performed at the Fraunhofer ISE Calibration Laboratory

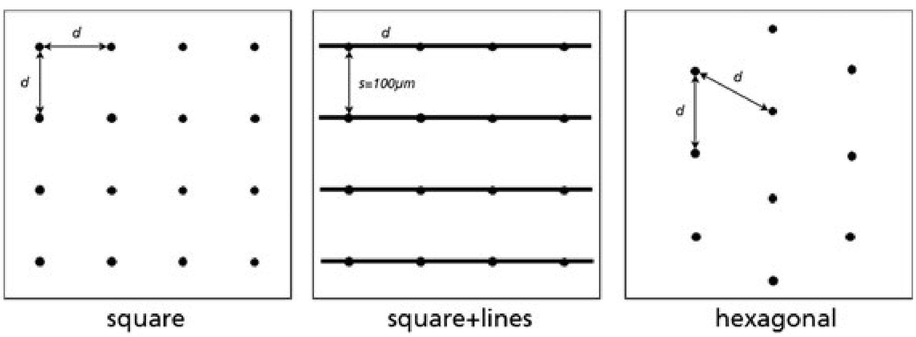

Figure 2. Three different via layouts have been realised to compare the performance under concentrated illumination. Line pitch for the 'square + lines' design was kept constant at 100 µm.

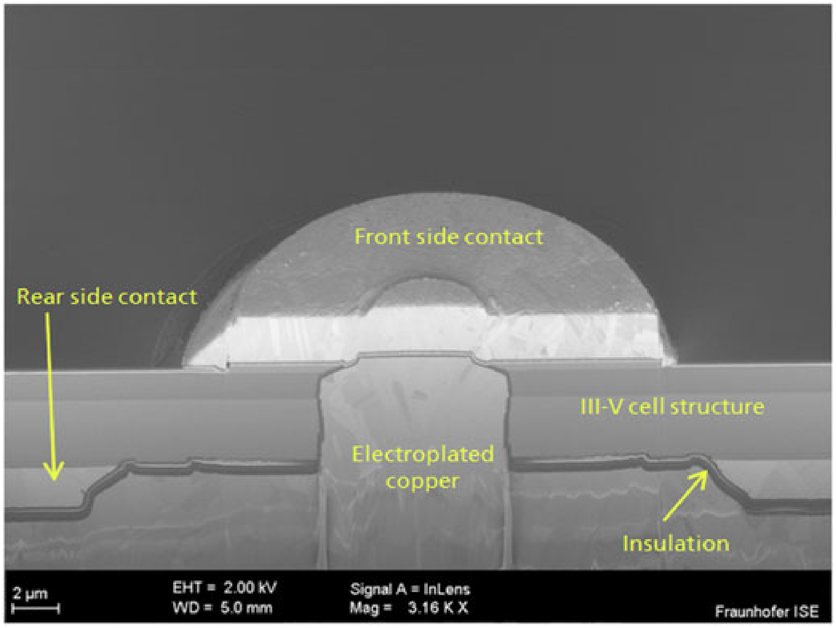

Figure 4. Scanning electron microscope cross-sectional image of a front contact and via hole filled with copper and insulated from the GaInP/GaAs tandem cell structure.

(ISE CalLab PV Cells). External quantum efficiency data for the dual-junction cell structure are given in Figure 5, which shows good carrier collection in the spectral range of both subcells. The measurement has been performed on an MWT solar cell. Calculated currents under the AM1.5d standard solar spectrum are 13.3 and 12.3 mA cm^{-2} for the top and bottom subcells respectively. The current mismatch of 7.7% exhibits a potential for further optimisation.

One-sun IV characteristics under the ASTM G173-03AM1.5d spectrum (normalised to 1000 W m^{-2}) for MWT tandem solar cells with different via pitch and layout have been measured at $T = 25\,°C$ by using a spectrally matched three-source sun simulator [19]. Measurement results for three cells with hexagonal via arrangement and via pitch of 50, 100 and 200 µm are shown in Figure 6.

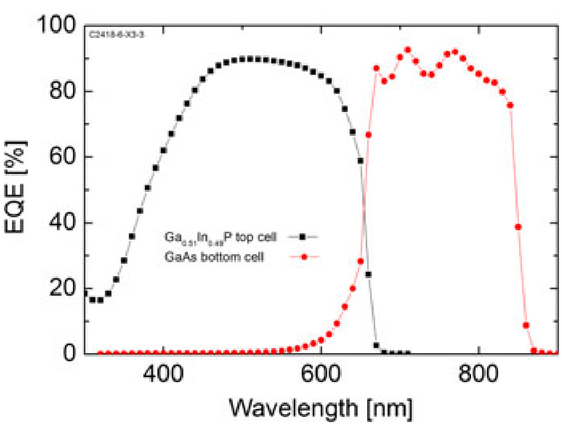

Figure 5. External quantum efficiency for a GaInP/GaAs dual-junction MWT solar cell.

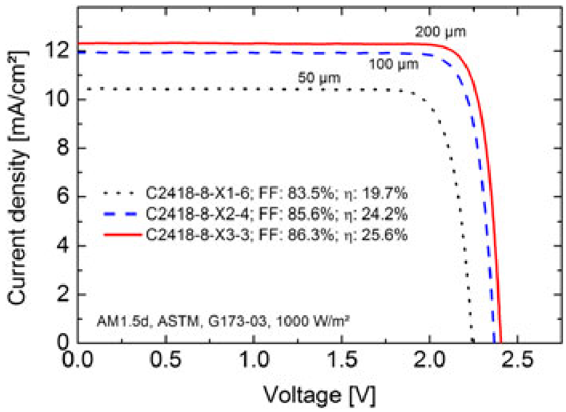

Figure 6. One-sun IV characteristics of three MWT cells (0.183 cm^2 total area without busbar) with hexagonal via array and different via pitch. All cells were processed on the same wafer.

Excellent IV characteristics are found with fill factors (FFs) between 83 and 86%, indicating a high shunt resistance. The highest performance with an efficiency of 25.6% is obtained for a device with 200 µm pitch (total area without backside contact pad which is outside the cell mesa area). Open-circuit voltage (V_{oc}), short-circuit current and FF are reduced for a pitch of 100 and 50 µm. The reduction in current is attributed to additional metal shading, whereas the drop in V_{oc} and FF can be explained by increasing perimeter with the number of metal vias. The additional surface surrounding the metal vias leads to an increase of the dark saturation current and consequently influences the measured V_{oc}.

Some MWT solar cells show a high loss in V_{oc} and FF, as can be seen from Figure 7 (left). This behaviour indicates a low shunt resistance for one of the subcells. Electroluminescence characterisation was carried out, and a bright luminescence appears at the origin of one of the vias. Subsequent scanning electron microscope focused ion beam analysis confirmed that a damaged via hole filled with front side metallisation has caused this local shortcut.

The fabricated MWT solar cells were further characterised under concentration by using a single-flash simulator. The flash spectrum leads to an excess current generation in the GaInP top cell of approximately 10% compared with AM1.5d which may result in a slight overestimation in FF as described in Ref. [20]. Figure 8 compares two of the devices with hexagonal via array (50 and 200 µm pitch from Figure 6) with two additional cells with 'square' or 'square + lines' pattern. The V_{oc} of all devices increases under concentration, but it can also be seen that the cell with the highest density of metal vias (50 µm pitch, hexagonal) experiences a steeper increase in voltage, approaching nearly the values of cells with 100 µm pitch at 1000 suns. This indicates that the voltage loss at one sun, attributed to the high perimeter area of cells with dense vias, is saturated under concentration. In fact, the power of the hexagonal MWT cell with 50-µm pitch outperforms the cell with 200-µm pitch for $C > 400$ due to a lower series resistance loss, indicated by the higher FF. Unfortunately, the hexagonal MWT cell with 100-µm pitch did not survive the measurement and therefore we have included an alternative cell with squared via pattern

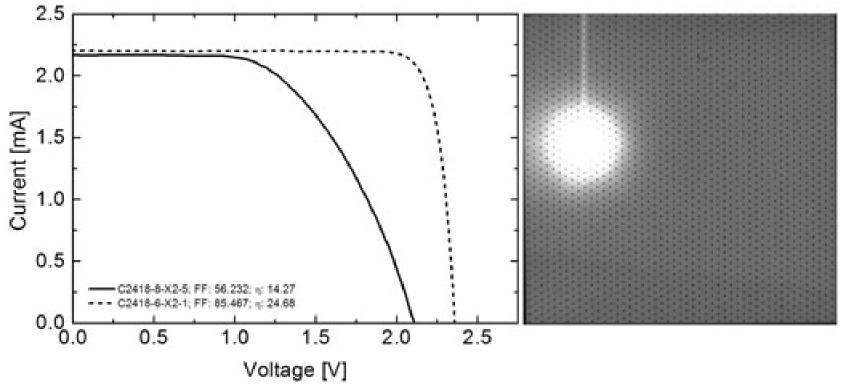

Figure 7. Comparison of two MWT cells with identical layout but significant difference in the IV characteristics (left). Electroluminescence image of an MWT cell (full line in left figure) showing strong luminescence from a shunted via (right).

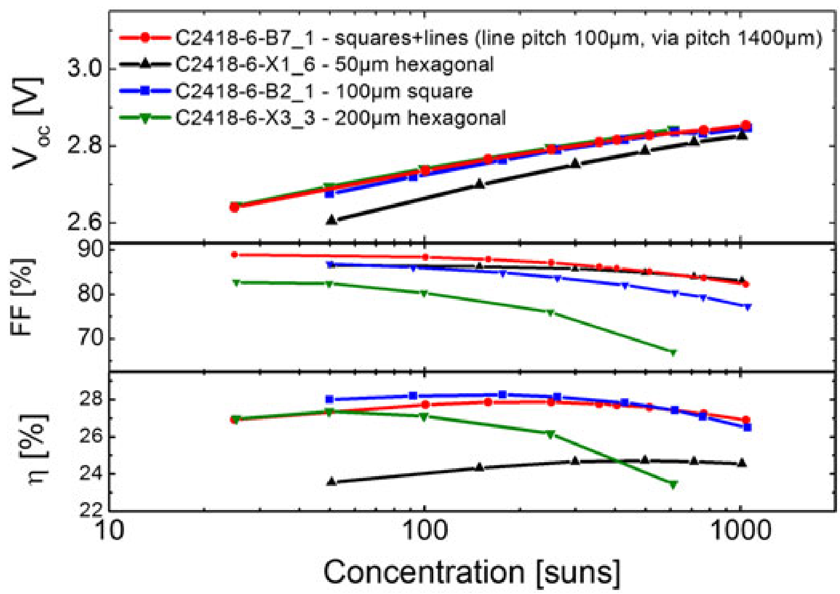

Figure 8. Efficiency, fill factor and open-circuit voltage versus concentration for selected MWT solar cells. The cell size is 18.3 mm^2, via pitch and layout: X1-6, 50 µm hexagonal; B2-1, 100 µm square; X3-3, 200 µm hexagonal; and B7-1, 'square + lines' design (line pitch 100 µm, via pitch 1400 µm).

and 100-μm pitch. The difference between hexagonal and squared via arrays is expected to be negligible, and in fact, this device shows characteristics in FF and voltage which are well between the hexagonal cells with 50 and 200 μm pitch. One can see that this cell outperforms the former devices over a wide concentration range of 50–1000 suns and reaches a maximum efficiency of 28.3% at 176 suns. This is an excellent achievement for the first MWT solar cells.

Figure 8 also shows the result of an MWT cell with additional metal fingers connecting the vias on the front surface. These metal grid lines are expected to reduce losses due to lateral current conduction in the GaInP emitter. At the same time, the distance between vias could be reduced to 1400 μm which leads to significantly less surface area. In fact, the device shows the highest V_{oc} and FF at low concentration, but the current is slightly lower due to shading of the grid fingers. At very high concentration factors of 700 suns and above, this device outperforms all other MWT cells and reaches an efficiency of 27.2% at 800-fold concentration.

5. SUMMARY AND CONCLUSIONS

An MWT technology was developed for III–V multi-junction solar cells to demonstrate large-area devices operating at high sunlight concentration levels. Shadowing losses for concentrator cells at 800-fold concentration were calculated to be below 4% and independent of the device area. MWT cells based on an inverted GaInP/AlGaAs dual-junction cell structure were realised. The best MWT devices with an area of 18.3 mm^2 already reach an efficiency of 28.3% at 176 sun and 27.2% at 800 sun concentrations without visible shunts in electroluminescence images. Further improvement of the device performance is expected after adjusting the current matching and improving materials. GaInP/GaAs tandem cells with efficiencies up to 32.6% have been published [21], and the performance may be even increased beyond 40% by adding additional junctions [22,23]. Therefore, the MWT technology offers an attractive high-performance pathway for solar concentrator applications requiring large-area devices at high illumination intensities.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge and thank Rita Freitas, Ranka Koch and Annika Schuette for device processing and Gerald Siefer, Elvira Fehrenbacher, Alexander Wekkeli and Yannick Schreiber for electrical characterisation. This work was funded by the Fraunhofer-CEA VirtualLab project.

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DOI: 10.1002/pip