III-V MULTI-JUNCTION METAL-WRAP-THROUGH (MWT) CONCENTRATOR SOLAR CELLS

E. Oliva[*], T. Salvetat[#], C. Jany[#], R. Thibon[#], H. Helmers[*], M. Steiner[*], M. Schachtner[*], P. Beutel[*], V. Klinger[*],
J.S. Moulet[#] and F. Dimroth[*]
[*]Fraunhofer Institute for Solar Energy Systems ISE, Heidenhofstraße 2, 79110 Freiburg, Germany
[#]CEA, LETI, Minatec Campus, F-38054 Grenoble, France

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 metallization and ohmic resistance losses in the metal grid limit the practical cell size typically to around 1 cm^2 at 800 suns. The use of a full back-contact architecture, similar to the Metal Wrap-Trough (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 realization of dense array receivers with low metal shadowing. The MWT technology addresses conventional concentrating photovoltaics as well as combined PV-thermal applications and offers specific advantages for large area devices at high intensities. This work presents 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.

Keywords: III-V Semiconductors, Back Contact, High-Efficiency, Multi-junction Solar Cell, Concentrator Cells

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 in space for powering satellites or on earth in high concentration photovoltaics (HCPV) systems or in optical power transmission [1, 2]. Four-junction solar cells with record efficiency up to 46.1% (at 312xAM1.5d) have been demonstrated [3] using wafer bonding technology but several other device architectures had been suggested and demonstrated [4-6]. This includes inverted four-junction solar cells which reached efficiencies up to 45.6 % (at 690xAM1.5d) [7] Typical concentrator solar cell devices in HCPV modules have dimensions of 1 mm^2 up to 1 cm^2 and operate at concentration levels between 200 and 1500 suns. Larger area devices are used in parabolic dish mirror systems within dense array receivers [8, 9]. Such receivers may cover an area of 100 cm^2 up to 1 m^2 and operate up to an intensity of 1 MW/m^2 equivalent to 1000 suns. Ohmic resistance losses scale with the square of the current and therefore become a major concern for large area, high concentration devices. The ohmic resistance 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 minimize shading and resistance losses for large area devices at high concentration levels [10, 11]. Such approaches limited the current through series connection and higher voltage but require trenches for the interconnection which lead to additional inactive area.

The challenge of high currents and metal shading in silicon photovoltaics has led to the development of metal-wrap-through (MWT) technologies in which the emitter and base contacts are both realized 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 efficiency up to 21.0% (AM1.5g) [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 realization of such devices is complex. In this paper we discuss how we adapt the MWT technology to realize first functional devices in an inverted Ga$_{0.51}$In$_{0.49}$P/AlGaAs tandem solar cell. We further show the influence of design variables like via pitch and pattern. And we discuss the influence of local shunts on the characteristics of concentrator solar cells.

2 BENEFITS OF CONCENTRATOR MWT CELLS

The task of optimizing 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 finger shape for sidewall reflection of photons into the solar cell are typical design variables. Such a front contact grid optimization has been performed at Fraunhofer ISE for GaInP/AlGaAs dual-junction solar cell devices using SPICE network simulation. Detailed descriptions of this modelling method can be found in [16]. Shading losses by the contact grid metallization with different geometries optimized 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 1x1 cm^2 device with a 10 μm x 2.7 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.

The metal-wrap-through-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 [17]. The absolute efficiency improvement for a 0.49 cm^2 triple-junction GaInP/GaInAs/Ge solar cell at high concentration levels of 500-2000 suns is estimated to be in the range of 1.9-3.0% compared to a conventional design [17]. Higher

gains are possible for larger cells and higher concentration levels. An efficiency improvement of 10% (4% absolute) at 500 suns was calculated in [15] for GaInP/GaAs/GaInAs inverted metamorphic (IMM) triple-junction solar cells. Furthermore, a dry etching process for the formation of via-holes in IMM structures has been successfully demonstrated in [15].
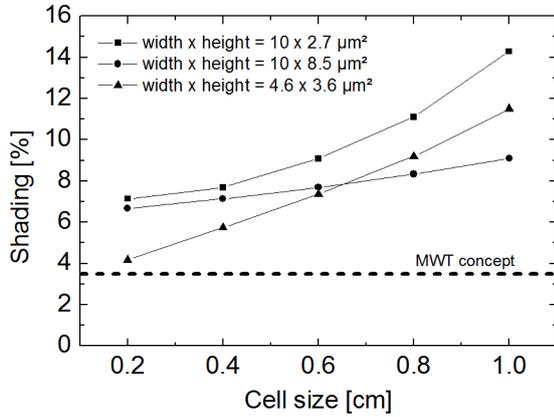

Figure 1: Shading by the front contact grid calculated for a GaInP/AlGaAs tandem solar cell optimized for 800 sun concentration of the AM1.5d spectrum and different metal finger geometries.

We conducted a simulation based on the 2-diode-model and experimental data for 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 obtained for 800-fold concentration is 3.5 % as presented in

Figure 1 by the dotted line. One can see that the MWT technology offers significant advantages in 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 substrates using an AIX2800G4-TM metal-organic vapour phase epitaxy (MOVPE) reactor with an 8x4" configuration. The hydride sources arsine and phosphine were used for the group-V growth. TMGa, TMIn and TMAl were the group-III precursors. Doping sources were DMZn, DETe, DTSe, SiH_4 and CBr_4. 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 530-680 °C and the reactor pressure was between 50-100 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 $Ga_{0.51}In_{0.49}P$ 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 subcells have 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 interconnected 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 > $5x10^{18}$ 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 $1-6x10^{-6}$ Ohm 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 shown in Figure 2. The metal vias were arranged in a squared 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.
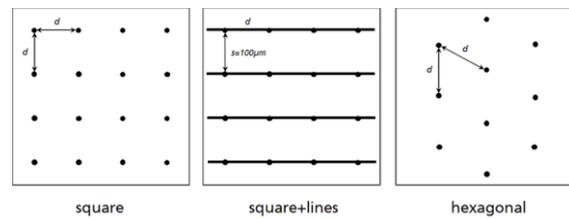

Figure 2: Three different via layouts have been realized to compare the performance under concentrated illumination. Line pitch for the 'square+lines' design was kept constant at 100 μm.

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, first an ohmic planar back contact was evaporated, followed by dry etching of vias with a diameter of 10 μm. The surface of the metal and the vias were conformal coated with insulating Si_3N_4/SiO_2 and TiN as 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 epitaxial growth of the tandem cell and for mechanical stability) was removed to give access to the GaAs cap. After opening the vias from the top, the GaAs cap layer war etched around the vias and a 2-layer Ta_2O_5/MgF_2 anti-reflection coating was evaporated and structured. As next an ohmic metal contacts were applied with the geometry shown in Figure 2. Finally the cell area was defined by the etched mesa area.

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 [18]. It has to be mentioned that the current cell design has not been realized 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 minimize shading on large area concentrator solar cells. A substantial number of 4.2x4.2 mm² and 9.5x9.5 mm² MWT cells have been processed for testing.
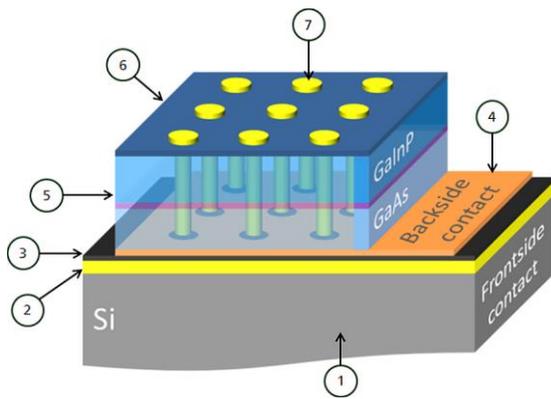
Figure 3: Schematic illustration of the MWT cell architecture with: 1 – silicon carrier, 2 – electroplated copper, 3 – Si_3N_4/SiO_2 insulation (black), 4 – back side contact, 5 – GaInP/AlGaAs tandem solar cell structure, 6 – Ta_2O_5/MgF_2 anti-reflective coating (ARC), 7 – front side contact connected 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 as well as the rear side contact metallization. The diameter of the front ohmic metallization is relatively large (~23 µm) and could be reduced in the future to about 15 µm. The width of grid lines has been 5 µm for the "square+lines" design.
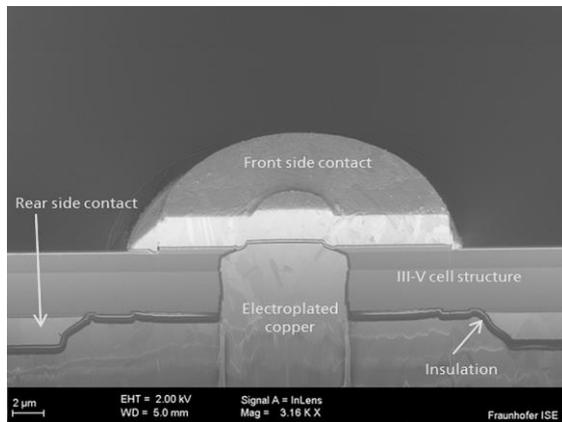

Figure 4: SEM cross-section image of a front contact and via-hole filled with copper and insulated from the GaInP/AlGaAs tandem cell structure.

4 RESULTS AND DISCUSSION

Electrical characterization of processed devices was performed at the Fraunhofer ISE Calibration Laboratory (ISE CalLab PV Cells). External quantum efficiency (EQE) data for the dual-junction cell structure is given in Figure 5 and it shows good carrier collection in the spectral range of both sub-cells. The measurement has been performed on a MWT solar cell. Calculated currents under the AM1.5d standard solar spectrum are 13.3 mA/cm^2 and 12.3 mA/cm^2 for the top and bottom subcell, respectively. The current mismatch of 7.7% exhibits a potential for further optimization.

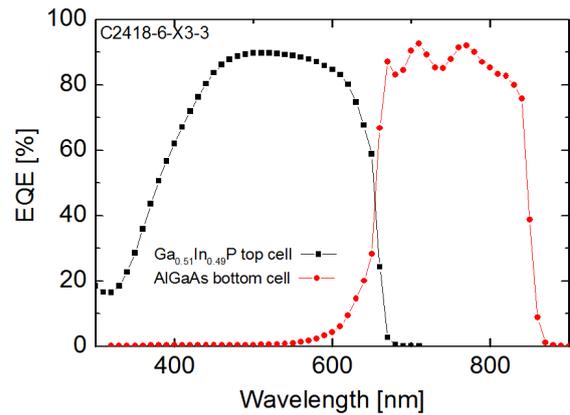**Figure 5:** External quantum efficiency for a $Ga_{0.51}In_{0.49}P/Al_{0.03}Ga_{0.97}As$ dual-junction 4.2x4.2 mm² MWT solar cell.

One-sun IV-characteristics under the ASTM G173-03 AM1.5d spectrum (normalized to 1000 W/m²) for MWT tandem solar cells with different via pitch and layout have been measured at T=25 °C 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.
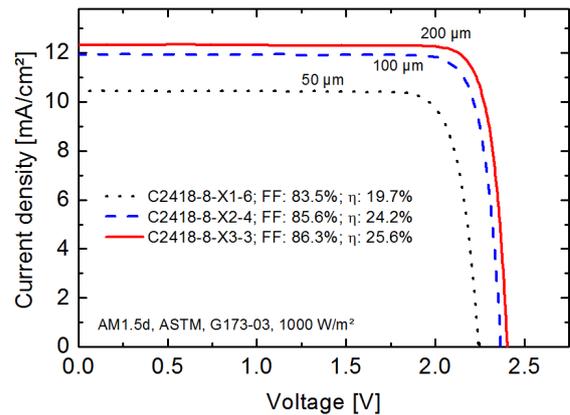

Figure 6: One-sun IV-characteristics of three MWT cells (0.183 cm² total area without busbar) with hexagonal via array and different via pitch. All cells were processed on the same wafer.

Excellent IV-characteristics are found with fill factors between 83-86 % 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 I_{sc} and fill factor 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 an increasing perimeter with increasing 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 fill factor as illustrated by the I-V curves in Figure 7 (left). This behavior indicates a low shunt resistance for one of the sub-cells. Electroluminescence (EL) characterization was carried out and a bright luminescence appears at one of the vias. Subsequent

SEM-FIB analysis confirmed that a damaged via-hole filled with front side metallization has caused this local short-circuit.
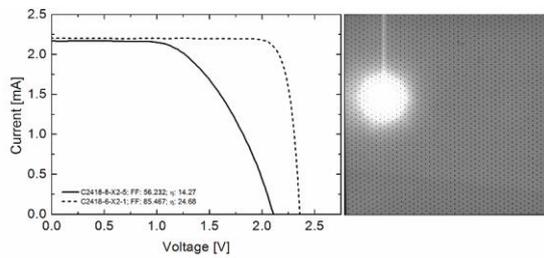

Figure 7: Comparison of two MWT cells with identical layout but significant difference in the IV-characteristics (left). Electroluminescence image of a MWT cell (full line in left figure) showing strong luminescence from a shunted via (right).

The fabricated MWT solar cells were further characterized under concentration using a single-flash simulator. The flash spectrum leads to an excess current generation in the GaInP top cell of approximately 10 % compared to AM1.5d which may results in a slight overestimation in fill factor as described in [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. Also it can be seen that the cell with the lowest V_{oc} and highest density of metal vias (50 µm pitch, hexagonal, black triangles) experiences a steeper increase in voltage, approaching nearly the values of cells with 100 µm pitch at 1000 suns. This indicates that the negative voltage effect at one-sun, which was attributed to the high surface 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 which is also indicated by the higher fill factor. 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 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 fill factor and voltage which are well between the hexagonal cells with 50 and 200 µm pitch. One can see that 100 µm via pitch 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 a 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 top cell 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 fill factor at low concentration but the current is slightly lower due to the additional shading from 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.
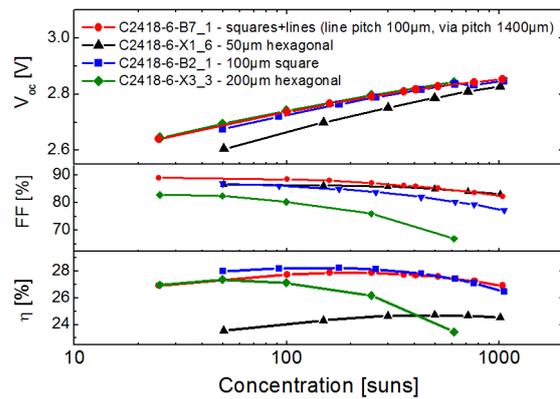

Figure 8: Efficiency, fill factor and open-circuit voltage versus concentration for selected MWT solar cells. The cell size is 18.3 mm², via pitch and layout: X1-6 – 50 µm hexagonal, B2-1 - 100 µm square, X3-3 – 200 µm hexagonal, B7-1 – "square+lines" design (line pitch 100 µm, via pitch 1400 µm).

5 SUMMARY AND CONCLUSIONS

A Metal Wrap Through 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 realized. The best MWT devices with an area of 18.3 mm^2 reach an efficiency of 28.3 % at 176 suns and 27.2% at 800 suns concentration without visible shunts in electroluminescence images. Further improvement of the device performance is possible by adjusting the current matching and by adding additional junctions [21, 22]. Therefore, the MWT technology offers an attractive high performance pathway for solar concentrator applications at high illumination intensities. Candidates are dense array receivers in parabolic dish or solar tower applications.

6 ACKNOWLEDGEMENTS

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