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METAL WRAP THROUGH SILICON HETEROJUNCTION SOLAR CELLS AND FIRST MADE MINIMODULES

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ABSTRACT: In this paper we present the successful integration of a silicon heterojunction (HJ) solar cell with metal wrap through architecture (MWT) and foil based- back contact module technology. With this contribution we show a record cell efficiency of 20.3% achieved using commercial n-type Cz 6 inch wafers and demonstrate an encapsulated cell efficiency of 19.6% achieved on a 2×2 mini-module. To our knowledge this is the first time that module results of MWT-HJ architecture have been reported. In this studies , we propose a method to increase the solar cell performance up to 21% together with a 50% cost of ownership reduction of the front silver metal including via and conductive adhesive. This is possible solely by the optimization of the front metal grid. MWT-HJ is a fully low-temperature integrated cell and module concept compatible also with thinner wafers.

Keywords — silicon, heterojunction, photovoltaic cells.

1. INTRODUCTION AND BACKGROUND

High efficiencies and low materials consumption are the main drivers towards low-cost ($/Wp) silicon PV modules.

Several solar cell technologies have demonstrated the ability to reach more than 20% cell efficiency. In addition, new back contact module technologies are now available to overcome losses caused by the interconnection and due to the limited width of the tabs.

In this contribution we demonstrate the successful combination of Metal Wrap Through (MWT) structure with Heterojunction (HJ) solar cells and foil based- back contact module technology [1].

The vast majority of the market implements module technologies based on interconnection of solar cells in strings by tabs soldered from the front of one cell to the rear of the adjacent one. To limit shading losses caused by these tabs, such interconnection leads to additional resistivity losses in a string of cells thereby reducing the module performance. MWT technology provides a relatively small step from conventional cell technologies and has already demonstrated to increase the module power by 3%, and up to at least 5% is anticipated [2]. This is possible thanks to an integrated cell and module design in which conductive interconnection foil is used to reduce the cell-to-module power loss compared to conventional tabbing technology. Part of this gain is thanks to the reduced metal coverage on the front side, giving the solar cell performance a potential efficiency increase up to about 2.5% relative. Furthermore, thanks to the unit cell concept (the front contact of each unit cell connected to a rear contact by a through-cell via) an MWT cell structure decouples the wafer size from metallization requirements allowing for better cell-to-module power ratio.

Front and rear contacts heterojunction solar cells have demonstrated more than 24% cell efficiency (25.6% on interdigitated back contact [4]) achieving excellent surface passivation with Voc exceeding 730 mV [3]. This has an impact on the temperature coefficient as well, resulting in higher module output power under real operating conditions. Nevertheless the low temperature Ag paste required for contact formation in HJ devices is still a challenge as it suffers from low conductivity resulting in high Ag consumption. Solutions such as multi-wire interconnection and multi-busbars have been introduced to tackle this conductivity issue [5,6]. MWT-HJ architecture provides an alternative solution to the reduced conductivity of low temperature silver pastes while maintaining the above mentioned advantages.

Moreover, the low-temperature process required by heterojunction is perfectly met by the foil based - back contact module technology, which uses conductive adhesive and single step curing for interconnection and encapsulation. MWT and HJ cell technologies are also compatible with next generation thinner wafers resulting in a win-win situation both on cell and module level.

MWT-HJ devices combine all the advantages of the individual concepts in a device with high open circuit voltage, high short circuit current and high module power thanks to reduced power loss. Recent modeling of this cell architecture also predicted these attributes [7,8]. In this paper, we show results of this MWT-HJ solar cell architecture with a record efficiency of 20.3% [9] made by 6 inch wafers and a 2×2 mini-module with encapsulated cell efficiency of 19.6%. This module has a cell to module (CTM) efficiency loss (~0.7%$_{abs}$.), which is suprisingly good comparing to the conventional state of the art heterojunction solar cell modules [10]. To our knowledge this is the first time that module results of MWT-HJ architecture have been reported.

Figure 1. Image of the MWT-HeteroJunction solar cell.

2. CELL AND MODULE CONCEPT

2.1 CELL CONCEPT

MWT solar cells have the same architecture of a conventional solar cell with the addition that the front metal contact is wrapped through the wafer through metallised via holes, providing both emitter and base contacts on the rear side (Fig. 1). As the cell interconnection does not require tabbing the busbar can be significantly slimmed down enhancing the light harvesting in comparison to conventional H-pattern cells.

In a front emitter MWT-HJ cell structure the possibility of a reduced shunt resistance between the front metal contact and the base exists as shown in Fig. 2 unless the via metal and the rear-side emitter contact pad are stacked on an emitter layer, or isolated from the base in another way. This will result in complex processing requirements. In the configuration with a rear emitter the front side metallization is still in contact with the dead emitter. But cell voltages below Voc this only leads to limited additional recombination since the supply of holes is limited as the base does not contribute much to the hole transport and the a-Si:H layer has very limited lateral conductivity. Further rear side optimization can reduce this recombination current [9]. Fig. 2 shows the rear emitter structure adopted for this MWT-HJ solar cell [11].

A rear emitter HJ device has other advantages, without the optical constrain for p-type a-Si:H as window layer, a sufficiently doped and thick p-type a-Si:H layer can be envisaged: i) the open circuit voltage can be improved and the field effect surface passivation enhanced [12] without increasing first pass light absorption; (ii) the fill factor could be further improved; iii) a stronger band bending in favor of charge transport at the n-type c-Si/p-type a-Si:H interface and at the p-type a-Si:H layer/ transparent conductive oxide (TCO) interface can be realized [13],[14]; (iv) the conductivity requirements of the front side TCO are reduced [15].

A rear emitter device necessarily has an extra requirement regarding the wafer diffusion length as the majority of the photons are absorbed in the vicinity of the front side and the generated minority carriers have to diffuse to the rear side before to be separated. We fabricated front and rear emitter H-pattern solar cells as baseline process for the MWT-HJ and to verify the material requirements. By solely reversing the device architecture and using commercial Cz wafers we obtained equivalent IQE at wavelengths in the 800-1200 µm range demonstrating that up to now material requirements are fulfilled by commercially available wafer technology. Nevertheless in general high efficiency devices require larger diffusion length than conventional state of the art devices due to the superior surface passivation implemented [16] and this has to be taken into account in any advanced concept.

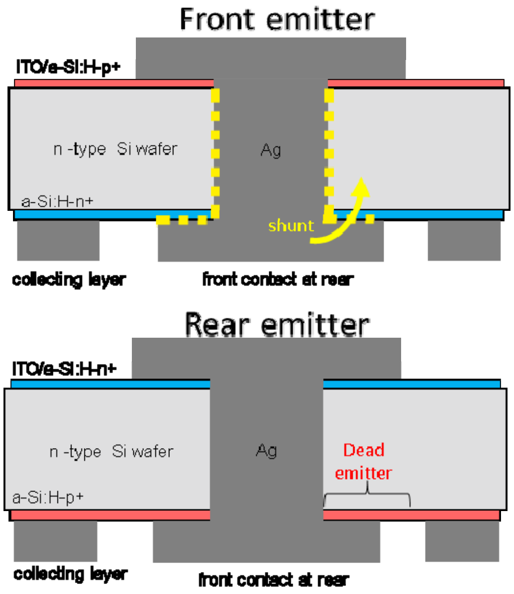


Figure 2. Structure of a front (top) and rear (bottom) emitter MWT-HJ solar cell. The diagram is not in scale. The collecting layer represents both the ITO and Ag rear contact.

2. 2 MODULE CONCEPT

Foil based - back contact module technology has been developed with an easy approach for MWT solar cell encapsulation [1]. The module technology requires conductive back sheet foil and conductive adhesive for

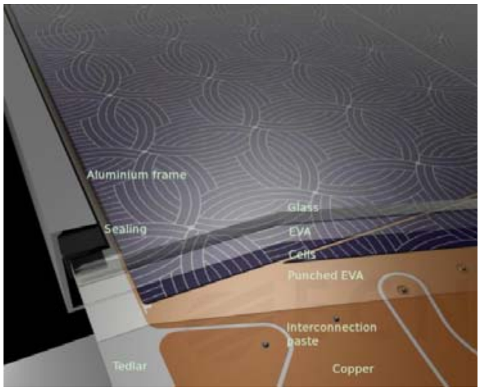


Figure 3. Cross section of the foil-based back-contact module with MWT cells.

interconnection as seen in figure 3. The conductive adhesives are cured during the lamination process. The main advanges of this module technology are: a) lower cell to module (CTM) power loss comparing to H-pattern module made by tab-soldering; b) a low temperature interconnection and encapsulation in one single step (<200°C) compatibile with Si heterojunction solar cell technology; c) suitabilitye for thinner wafers, therefore, it offers a solution PV modules cost reduction.

3. EXPERIMENT RESULTS AND PROCESS FLOW

6” industrial n-type Cz monocrystalline silicon wafers about 180 µm thick were used as substrate for MWT-HJ solar cell fabrication. After texturisation and dedicated surface cleaning, wafers were loaded into an AK1000 tool (manufactured by Roth and Rau AG), in which the intrinsic and doped a-Si:H layers were deposited by plasma enhanced chemical vapor deposition (PECVD). The ITO layers and rear Ag blanket contact were produced by physical vapor deposition (PVD) in a second AK 1000 tool. Surface passivation quality was controlled by measuring effective lifetime of minority charge carriers and implied Voc on MWT-HJ cell precursors right after PECVD deposition. The metallization was realized by screen printing with low temperature silver paste followed by a curing step. The a-Si:H and ITO layer thickness and conductivity are typical for conventional heterojunction solar cells. The MWT-HJ solar cell process is same as the HJ process with adding a few extra steps typical for MWT cell technology: vias drilling, via filling and isolation of the two metal contacts at the rear. In this experiment, the vias drilling is done before the surface preparation for the a-Si:H depositions, therefore the damage removal is done without adding any extra chemical step. In the MWT-HJ process used, it is not necessary an isolation of the metal plug from the underlying Si or a-Si:H layer as explained in the previous paragraph and as result from the simulation reported in the last paragraph. The via filling is done within the same printing step of the rear side pad. The H-pattern lookalike MWT used here is well suited to make loss comparison with H-pattern and is considered just as an intermediate step for the current development phase. We obtained a record efficiency of 20.3% as result of a very fast learning curve, showing the potentiality of this technology and Voc’s of more than 730 mV on multiple devices. Table I shows the in house measurement according to the ASTM-E948 norm using a Wacom class AAA solar simulator and spectral mismatch correction, reference cell calibrated at ISE CalLab and using the full cell area. The overall uncertainty on the measured efficiency is estimated to be 2.3%. A stable process has been estalished resulting in a narrow efficiency distribution among 28 cells as shown figure 4.

Table I. IV-parameters of record 6 inch solar cell (239 cm^2)

Record	V_{oc}	J_{sc}	FF	Efficiency	Pmax
MWT-HJ	734 mV	36.3 mA/cm^2	76.3 %	20.3 %	4.86 W

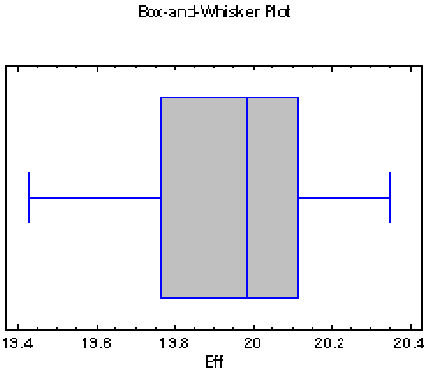
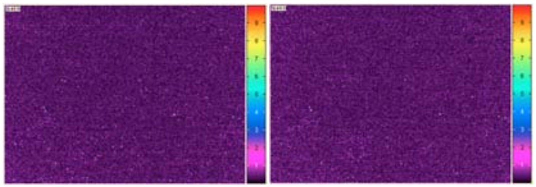


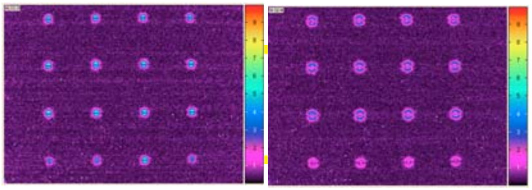
Figure 4. Box and whisker plot over the entire processed group of 28 cells.

Rear emitter MWT-HJ cell



0.5V forward 0.5V reverse

Front emitter MWT-HJ cell



0.5V forward 0.5V reverse

Figure 5. Lock In Thermography of a front emitter and rear emitter solar cell in forward and reverse currents. Scale in mK.

We manufactured front emitter MWT-HJ cells to verify our initial hypothesis of the different behavior with respect to shunts. These front emitter MWT-HJ cells are indeed strongly limited by shunt formation at the vias resulting up to now in 2% absolute lower efficiency. In Fig. 5 Lock in Thermography images of the front and rear emitter cell are reported. The advantage of the rear emitter MWT-HJ architecture with respect to the front emitter is shown on the ohmic shunt patterns around the vias.

A 2×2 mini-module with coated antireflection front glass has been successfully fabricated as shown in figure 6-a. The I-V characteristics by PASAN tester 2.1.2 in Table II show that an encapsulated cell efficiency of 19.6% has been reached on this 2×2 MWT-HJ mini-module. The illuminated area is restricted to 2 cm around the outer cell edges.

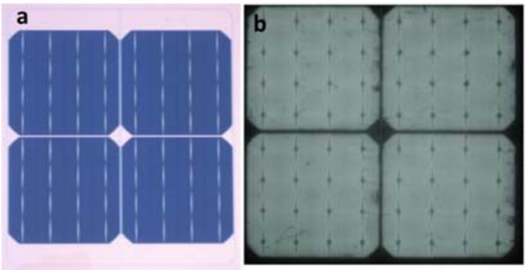
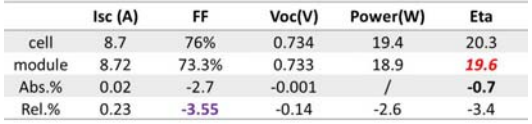


Figure 6. (a)2×2 MWT-HJ mini-module; (b)its electroluminence image

Table II. CTM of 2×2 MWT-HJ mini-module



	Isc (A)	FF	Voc(V)	Power(W)	Eta
cell	8.7	76%	0.734	19.4	20.3
module	8.72	73.3%	0.733	18.9	***19.6***
Abs.%	0.02	-2.7	-0.001	/	**-0.7**
Rel.%	0.23	**-3.55**	-0.14	-2.6	-3.4

The data in Table II also indicates that there is a cell to module (CTM) FF loss of ~3.5% rel, which seems very high as full-size regular MWT modules show a modest CTM FF change of -1.0%abs [2]. However, we typically observer CTM FF change of -2.5%abs for high quality 2×2 MWT mini-modules. Electroluminescence (EL) and DLIT data do not offer an explanation for this realtively high FF loss. Indeed, Figure 6-b shows a very good uniformity of the EL. All emitter and base contacts but no hot spots were observed in the DLIT measurement. We attribute the relatively high FF loss to current crowding the module connector, leading to resistive power loss. This power loss is constant, independent of the module size and therefore a small power loss on full-size modules can lead to relatively large FF losses for mini-modules. As a consequence, it leads to a much smaller percentage of power loss for a conventional 60 cells module than for a small 4 cells module [17]. In addtion, part of this FF loss can also be possibly attributed to non-optimized compatability between the conductive adhesives and the plug paste since this isour first demonstration experiment.

4. POTENTIAL MWT-HJ SOLAR EFFICIENCY

The low temperature Ag paste used for the metallization is a challenge for HJ cell processing. The reason is that the low temperature Ag line conductivity is about 3 times lower than the one for conventional fired pastes [18] and only few paste suppliers are currently available. As solutions, Cu plating and multi-busbar approaches in order to reduce the finger length have been investigated [19, 20, 21]. The latter has the double advantage to reduce both the Ag consumption and the series resistance losses on cell level at the same time. Here we propose the MWT cell design as an alternative method to reduce the resistive power losses and the silver consumption in heterojunction solar cells, matching with an integrated module technology.

The MWT solar cell structure is based on the concept of unit cells [22]. The advantage here is that the area of the unit cell can be optimized separately from the wafer size and replicated to cover the full cell area [23]. By reducing the unit cell area the resistive power losses are reduced, in principle, quadratically, therefore allowing for less metal coverage and giving more freedom to optimize the metal consumption versus cell performance. Increasing the number of vias not only reduces the finger length, but also the length of the BB in this H-pattern lookalike MWT front grid, and therefore since no tabs are placed on the front side, it reduces the BB resistive loss.

We calculated the impact of the unit cell area reduction, by increasing the number of vias without changing the full cell area. The effect for paste reduction and cell performance is similar to increasing the number of BBs for H-pattern front-to-back contact cells. However, interconnecting these multi bus bar cells requires machines that become more complex with increasing number of bus bars. On the contrary, the foil based – back contact module technology is perfectly compatible with high number via design .

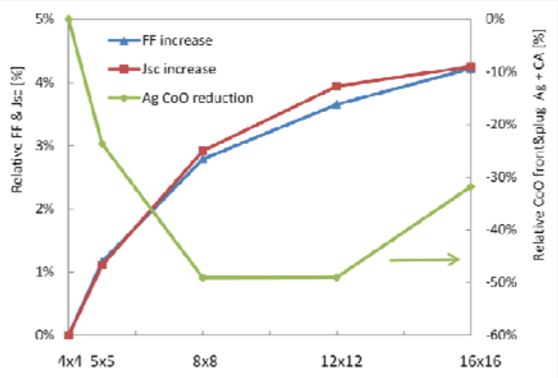


Figure 7. Calculated FF, Jsc and reduction of the front contact silver including via and conductive adhesive (CA) variations as a function of the number of vias

Fig. 7 shows the FF and Jsc variations with the increasing number of vias per cell together with the cost of ownership (CoO) of the front contact silver including via and conductive adhesive (CA) used for front metallization, via and module interconnection. For each configuration the finger width has been reduced inversely to the number of vias per length (i.e. 100 µm finger width as base for the 4×4 structure reduced to 50 µm for the 8×8 structure) but keeping the same aspect ratio and optimizing with respect to the number of fingers and (tapered) BB width. The impact of the extra conductive adhesive and via metallization costs have also been included keeping same rear pad size. Indeed a small unit cell relaxes the requirements for finger cross section and the busbar conductivity (width) of the LT-Ag paste. A front metal+via+CA CoO reduction of about 50% is calculated with an 8×8 vias configuration leading to about 6% relative efficiency increase with respect to a 4×4 vias configuration. An efficiency potential of over 21% is estimated for the current processes by optimizing the front metallization only. Above 12×12, the relative CoO start to increase since the via paste and CA costs start to outbalance the front metal reduction cost. This multi-vias approach enables the front metallization optimization for high efficiency and/or Ag reduction. In addition it has a benefit on the rear Ag consumption for the same reason since the number of contact points will increase in the rear as well. The amount of metal in the rear side is expected to decrease resulting in a further Ag CoO reduction. The copper pattern on the conductive back foil can easily be adjusted from the standard 4×4 MWT configuration to accommodate the 8×8 vias configuration, with a computer-controlled patterning process, such as pattern milling or laser scribing [24,25]. However, with increasing number of vias, the area of dead emitter layers in the rear emitter MWT-HJ cell will increase with causing potential performance loss. We have not observed performance loss as the Voc of our MWT-HJ cells is similar to the Voc obtained in front and rear contact HJ solar cells (H-Pattern). Anyway we estimate the extent of this losses for increasing number of vias and provided suggestions for their mitigation [9]. It is important to note that according to the current results and the simulation, this concept results in solar efficiency greater of 21% by solely changing the front metallization configuration.

5. SUMMARY

In this paper we present the successful integration of a silicon heterojunction (HJ) solar cell with metal wrap through architecture (MWT) and foil based – back contact module technology. MWT-HJ devices combine all the advantages of the individual concepts in a device with high open circuit voltage, high short circuit current and high module power. The module technology has been proved to be perfectly in agreement with the low temperature requirements of HJ solar cells.

We demonstrated a encapsulate cell efficiency of 19.6% based on 2×2 mini- module made by high efficiency (>20%) MWT-HJ solar cells. We prove the advantages and ease of the rear emitter structure to avoid shunt losses and to approach a high performance solar cell and prove a good feasibility of foil based – back contact module technology for MWT-HJ module fabrication.

We propose a method to reduce up to 50% front contact silver consumption including via and conductive adhesive. An efficiency greater than 21% is predicted solely by the optimization of the front metal grid and MWT configuration.

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