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SMARTWIRE SOLAR CELL INTERCONNECTION TECHNOLOGY

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ABSTRACT: The SmartWire Contacting Technology (SWCT) is an innovative interconnection technology for crystalline silicon solar cells: standard busbars and ribbons are replaced by copper wires coated with a thin low melting point alloy layer and supported by a polymer foil. The SWCT provides key advantages: low temperature contacting during module lamination, increase in efficiency by lowering ohmic losses and enabling fine-line printing, reduced consumption of silver by 85 % or more, enhancement of module reliability (1000 to 2000 electrical contact points on each cell), and improved aesthetics. Automated production lines are today proposed by Meyer Burger, with a flip-flop connection avoiding previously used interconnection ribbons. The SWCT is well suited for module implementation of silicon heterojunction (SHJ) solar cells: 319.8 Wp and 327 Wp SWCT-SHJ module (20% total area efficiency) are reported, integrating SHJ solar cells produced at Choschu Industry Co. In addition, strong Ag usage reduction for monofacial (down to 10 mg Ag on the front side) as well as for bifacial SHJ cells (down to 15 mg per side) are demonstrated. High reliability is confirmed with < 5 % degradation for up to 4000 hours of damp heat and 800 thermo-cycling tests. Finally, further cost reduction potential is demonstrated with first results of replacement of state-of-the-art InSn wire coating by a BiSn alloy.

Keywords: Cells interconnection; Solar module technology; SmartWire; Metallization; Characterization

1 INTRODUCTION

The SmartWire Contacting Technology (SWCT) consists of copper wires supported by a polymer foil (see Figure 1) [1, 2]. The wires are coated with a thin low melting point alloy layer, which melts during the module lamination process and builds up a solder contact to the cell metallization. This approach was initially proposed by Day4 Energy [2]. It replaces state-of-the-art busbars and ribbons technology, and is applied to cells with front metallization not implementing busbars but solely fingers (see Figure 1), referred to as busbar-less cells.

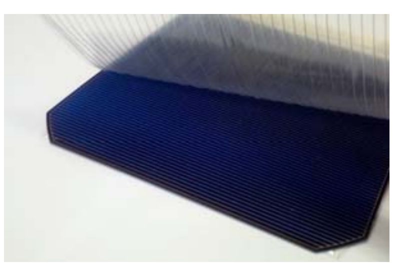

Figure 1: Picture of a SmartWire foil over a busbar-less cell.

The SWCT enables using more current extraction paths perpendicular to the cell metallic fingers than in standard busbar technology, thanks to a low wire optical dimension (typically about 140 µm per wire [1, 4]) and to its direct interconnection to the neighboring cell. This enables to go from the 2, 3 or 6 bus-bars typical schemes to more than 18 wires interconnection, as shown in Figure 2, without increasing shadowing losses.

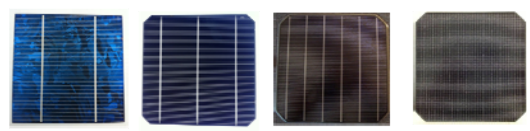

Figure 2: Evolution of standard c-Si cell contacting from 2 bus-bars, 3 bus-bars to 6 bus-bars and ultimately the SmartWire concept.

The SWCT processing conditions enable to carry out interconnection while remaining at low temperature, as this is actually realized during the module lamination, typically at a temperature of about 140-160 °C, i.e. below soldering temperature used with busbar-ribbon technology (see Figure 3), therefore inducing less thermo-mechanical stress on the cells.

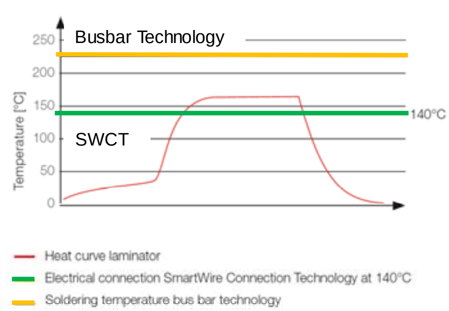

Figure 3: Temperature for connection with busbar technology, with SWCT as well as for module lamination.

The SWCT provides different key advantages, consecutive to this multi-wire usage and to these processing conditions.

First, the **SWCT leads to enhanced module performance and to reduced Ag usage** in the cell metallization. The use of multiple wire connections enables to **lower ohmic losses** in the cell metallization fingers. By using 18 wires (standard value for SWCT), the power loss (P_f) in the cell metallic fingers can be divided by 36 compared to a 3 busbars (BB) design if the other parameters are kept constant (equation 1), as the power dissipation losses in the finger, P_f, is inversely proportional to the square of the number of busbars:

$$P_f \propto \frac{J^2 L}{12 n_f} \frac{R_f}{n_{BB}^2} \propto C \frac{R_f}{n_{BB}^2} \quad (1)$$

J is the current density, L, the width of the cell, n_f, the fingers number, R_f, the finger line resistance, n_{BB} the busbar number and C a constant. This is further presented by Papet *et al.* [3], Braun *et al.* [4] and Mette [5].
As shown in equation 1, the increase in number of interconnection wires (busbars) enables the implementation of more resistive fingers than in state-of-the-art busbar cells. Similar power loss can therefore be achieved between 3BB design with initial finger line resistance and 18 wires design with finger line resistance 36 times higher than in the 3BB case. This permits the implementation of fine-line metallization, **reducing shadowing losses**, and a **drastic reduction in silver usage by 85 % or more [3], i.e. reduced costs**. Efficiency can further be improved with the SWCT thanks to the fact that no busbars nor soldering pads have to be implemented on the cell, which potentially reduces recombination losses.

Secondly, **high module reliability is achieved**. Each cell is contacted by 1000 to 2000 electrical contact points, enabling contacting of potentially broken cell pieces in the case of cracked cells, and guaranteeing conserved performance even in the case of few contacts lost. In addition, the limited interconnection temperature condition leads to reduced thermo-mechanical stress as no soldering step is needed, enabling the SWCT to be well suited for thin wafer cells interconnection.

Finally, the use of multiple thin wires instead of few large busbars gives SWCT module an **aesthetic improvement**, with a more homogeneous surface, as can be seen for instance in Figure 2.

This work focuses on the use of SWCT with silicon heterojunction (SHJ) solar cells, demonstrating the high performance achieved at module level and the high reliability demonstrated by such technologies combination (referred to as SWCT-SHJ in the following). It further presents the automated production line developed by the Meyer Burger group, with flip-flop interconnection avoiding previously used interconnection ribbons. Finally, further cost reduction potential is presented with the first results of replacement of the state-of-the-art InSn wire coating by a BiSn alloy, and by efficient implementation of cells with ultra-low Ag content.

2 SMARTWIRE CONTACTING TECHNOLOGY: KEY ENABLING TECHNOLOGY FOR SILICON HETEROJUNCTION SOLAR CELLS.

2.1 SWCT- HJT: high performance

Silicon heterojunction solar cells reach highest performance to date in crystalline silicon solar cell with up to 24.7 % demonstrated for standard SHJ cells and 25.6 % for IBC-SHJ cells [6]. The technology further triggers strong interest in the photovoltaic community as high efficiency, low thermal coefficient and cell bifaciality can be achieved at production level with a limited number of low temperature processes, and in turn at limited costs [9].

One of the SHJ technology limitation is the fact that low temperature Ag paste must be used, leading to higher printed line bulk resistivity when compared to state of the art high temperature Ag pastes. This latter property leads to about 180 mg Ag content usage in the front side of SHJ cells for busbar interconnection, and consecutively to increased costs of metallization for SHJ cells with busbars. The SWCT is therefore perfectly suited for the module integration of silicon heterojunction (SHJ) solar cells, as it enables the use of more resistive fingers as explained in section 1. With 18 wires usage, today's production can rely on below 40 mg of Ag for the front grid. In addition, soldering of low temperature silver paste attached on transparent conductive oxide (TCO) is a challenge. By using SWCT, this is further facilitated with the low temperature contacting temperature. By relaxing constraint on printed finger resistivity and owing to its low temperature contacting, the SWCT is therefore a key enabling technology for competitive silicon heterojunction solar modules production.

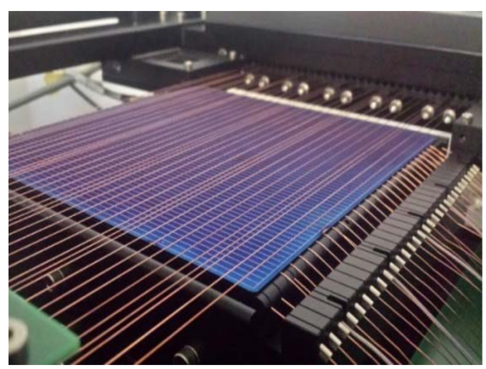

Figure 4: Full square 156 × 156 mm^2 SHJ cell produced by CIC measured using GridTouch® contacting developed by the company PASAN.

Full square 156 × 156 mm^2 SHJ bifacial cells produced by Choshu Industry Corporation (CIC) without busbars were measured using the GridTouch® contacting technology which was developed by the company PASAN to characterize busbar-less cells. A picture of a cell under the contacting set-up is shown in Figure 4. Details on CIC cells can be found here [11].

Nominal conversion efficiencies of 22.33 % were measured (see other parameters in Table 1). Using these

CIC SHJ cells, different SWCT modules with 60 cells were produced and results are summarized in Table 1. A first module using Gen1 SWCT was measured at 313 Wp, using 38 wires of 200 µm diameter for the interconnection. The best performance is achieved with 20 wires of 300 µm diameter: the Gen2 module shows a certified maximum power point (MPP) of 319.8 Wp (see Figure 5), while the Gen3 module, which implements a new electrode scheme, demonstrates a very high performance with a **certified MPP of 327 Wp (see Figure 6), corresponding to 20% module efficiency, one of the highest certified efficiency for a 60 cells modules.** .

CELL	***V_{OC}*** *(mV)*	***I_{SC}*** *(A)*	***FF*** *(%)*	***MPP*** *(W)*	***EFF*** *(%)*
Cell Grid Touch	728	9.41	79.2	5.43	22.33%
MODULE	***V_{OC}*** *(V)*	***I_{SC}*** *(A)*	***FF*** *(%)*	***MPP*** *(W)*	***CTM loss*** *(%)*
Gen1	44	9.1	78.2	313.1	4.0%
Gen2	44.01	9.4	77.3	319.8	1.8%
Gen3	44.01	9.5	78.2	**327.0**	-0.4%

Table 1: I-V performance of standard busbar less CIC SHJ cell measured with the GridTouch®. I-V performance of different SWCT-SHJ module generations. Gen1 uses 38 wires of 200 µm diameter, Gen2 20 wires of 300 µm diameter and Gen3 20 wires of 300 µm diameter with a new electrode scheme.

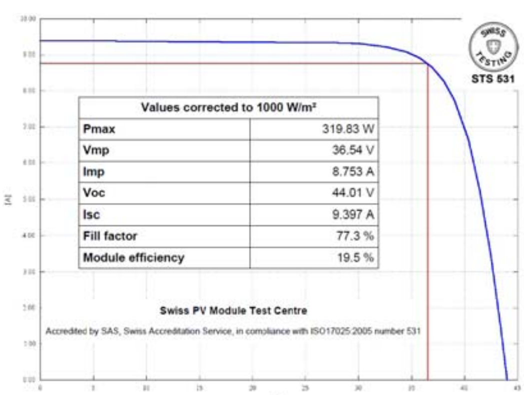

Figure 5: Certified IV curve of Gen2 module based on full square CIC SHJ cells and SmartWire Contacting Technology (SWCT). Certification was done by SUPSI Swiss PV Module Test Centre.

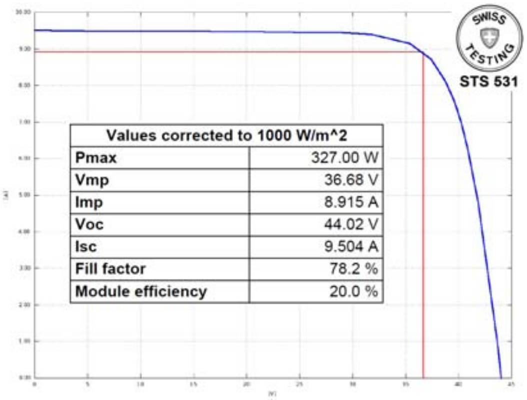

Figure 6: Certified IV curve of Gen3 module based on full square CIC SHJ cells and SmartWire Contacting Technology (SWCT). Certification was done by SUPSI Swiss PV Module Test Centre.

SHJ solar cells back surface can be designed with a back TCO layer and metallic fingers, resulting in a bifacial cell. These cells can be efficiently encapsulated in glass/glass bifacial modules by using the SWCT [8]. The high number of thin wires, in comparison to the busbar technology, is even more interesting for bifacial cells, for which a higher current has to be extracted from the cell thanks to its bifaciality (this can be up to 20 to 30 % more current), and for which metallic fingers are disposed both on the front and back side. Cost saving is therefore higher thanks to the reduced resistive losses in the fingers, with the potential to use low quantity of Ag both on the front and on the back sides of the SHJ cell. The SWCT can therefore enable production of SHJ bifacial modules at reduced costs, calculated < 0.5$cts/Wp.

While the high power of SWCT-SHJ was demonstrated with up to 327 Wp module, further advantages of the technology are highlighted in Figure 7 with in-field performance monitoring of state-of-the-art multi-crystalline silicon module, monofacial SWCT-SHJ module, and bifacial SWCT-SHJ module. The multi and HJT-Mono modules are glass white backsheet modules whereas the bifacial SWCT-SHJ module is a glass-glass module. All the modules were installed at SUPSI (Scuola universitaria professionale della Svizzera italiana) in Lugano during the spring and summer 2014. The 3 module technologies performance over 2 days in July is shown in Figure 7, while comparison over 20 days is reported in Table 2.

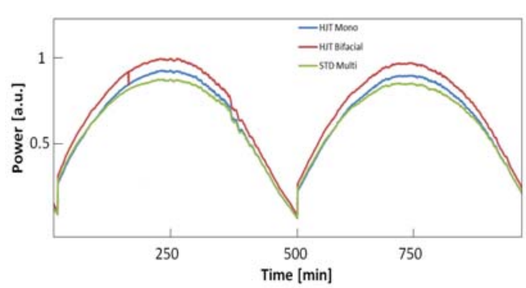

Figure 7: Power output of 3 different modules: multi-crystalline Si (STD Multi), heterojunction c-Si mono-facial (HJT Mono) and heterojunction c-Si bifacial (HJT Bifacial) over 2 days in July.

	Multi STD	*HJT Mono*	*HJT Bifacial*
Perfomance ratio Gain (%)	**0**	**2.7**	**15.3**

Table 2: Energy yield of 3 different modules: multi-crystalline Si (STD Multi), heterojunction c-Si mono-facial (HJT Mono) and heterojunction c-Si bifacial (HJT Bifacial) over 20 days in July.

2.2 SWCT – HJT : High Reliability

The state-of-the-art SmartWire technology proposed by Meyer Burger is based on the use of a thin Indium-Tin (InSn) coating on the wires, which enables modules with SWCT to have a highly reliable and efficient contacting between the wires and the cell metallization. The InSn eutectic coating contains 50.9 wt% In and 49.1 wt% Sn, it has a melting point of 120 °C, a low bulk resistivity of 14.4 μΩ.cm similar to PbSn alloys, a coefficient of thermal expansion close to pure copper and last but not least, its oxides are conductive [7]. While mechanical contacting can be sufficient to achieve a high efficiency module, metallurgical contacting is needed to guarantee a reliable and robust contacting, mainly to thermo-cycling tests. The InSn coating contacting to different variety of cell metallization materials and schemes was studied.

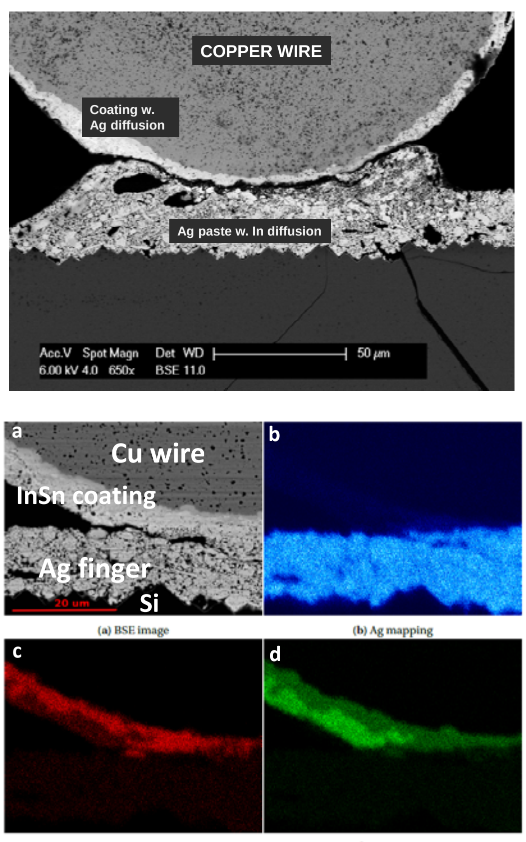

Figure 9: (a) Back scattered scanning electron microscopy (SEM) image and (b-d) energy dispersive x-ray spectroscopy (EDX) mapping of the contact between coated Cu-wire and low temperature silver paste.

Typical analysis by scanning electron microscopy of InSn coating contact to SHJ solar cell low temperature Ag printed finger are shown in Figures 8. The InSn coating (Figure 8c-8d) deforms during the lamination process to create a good contact to the silver finger (Figure 8a), which can itself also be deformed in the case of low temperature Ag paste (Figure 8 – top). The typical material structure from the wire to all tested cell metallizations was demonstrated to be: (1) Cu wire, (2) 1st intermetallic phase: $Cu_2(In,Sn)$ – Cu rich phase, (3) 2nd intermetallic phase: Cu_2In_3Sn – In rich phase, (4) remaining solder alloys: depleted in In – Sn rich phase and (5) finally the cell metallization (see Figure 10). For Ag front metallization, metallurgical bonding was evidenced with In diffusion in Ag and Ag diffusion in the Cu_2In_3Sn phase, enabling high bonding strength at the coating – metallization interface.

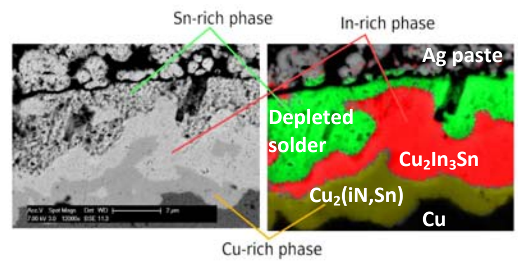

Figure 10: SEM-BSE image of the wires outer layer different phases. Wire coated contacted to low temperature silver paste (visible in the upper part of the image).

By using glass-glass (GG) module technology developed by Meyer Burger, 60 cells (156 × 156 mm² SHJ solar cells) modules interconnected with the SWCT demonstrate high reliability, with modules passing 4 times the IEC test standards, with a power output degradation of only -2.5 % after 800 thermo-cycles (-40 °C to 85 °C) and -1 % after 4000 hours in damp-heat (85 °C and 85 % relative humidity), see detailed performance results in Tables 3 and 4. These results demonstrate that modules with very high reliability can be produced using SHJ solar cells, as well as using SWCT interconnection, and combining the 2 technologies.

	Initial	***DH3000***	***DH4000***
Eff (%)	21.1	20.8	20.9
J_{SC} (mA/cm2)	37.6	37.0	37.2
V_{OC} (mV/cell)	731	733	733
FF (%)	76.8	76.7	76.7
Pmax (W)	308	304	305
Degradation	0.0	-1.3 %	-1.0 %

Table 3: Damp Heat (DH) IEC test of a glass-glass module with SWCT interconnection of 60 SHJ cells. Performance evolution up to 4000 hours of DH.

	Initial	***TC200***	***TC600***	***TC800***

Pmax(W)	274	273	270	267
I_{SC} (A)	8.21	8.18	8.21	8.27
V_{OC} (V)	43.17	43.2	43.4	43.5
FF (%)	77.4	77.0	75.7	74.8
Degradation	0.0	-0.4%	-1.6%	-2.5%

Table 4: Thermo-Cycling (TC) IEC test of a glass-glass module with SWCT interconnection of 60 SHJ cells. Performance evolution up to 800 TC.

2.5 SWCT: AUTOMATED PRODUCTION LINE

A new generation of automated production line for SmartWire Interconnection was developed. The equipment developed by Meyer Burger is a line concept as shown in Figure 11 where the SHJ SWCT-GG bifacial modules can be produced. The line is currently being built in Switzerland and the first modules have been successfully produced.

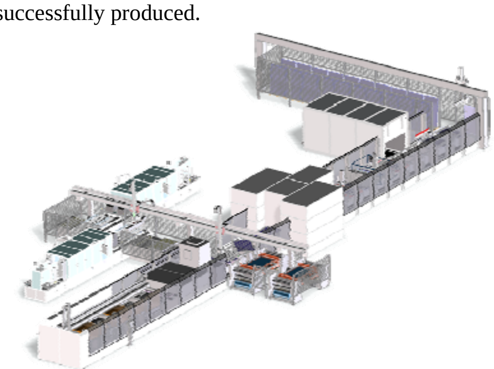

Figure 11: SWCT-GG module line with a 90 MW production capacity.

The SmartWire foil implementation design is shown in Figure 12 and 13, based on a concept used in typical stringing automated equipment. With the developed automated concept, the wires can directly interconnect the front side of one cell to the back side of the neighboring cell, without the need of any ribbon as was previously the case with the manual implementation proposed by Day4 Energy. This new concept is referred to as flip-flop and permits to reduce material cost and to have a closer cell to cell spacing.

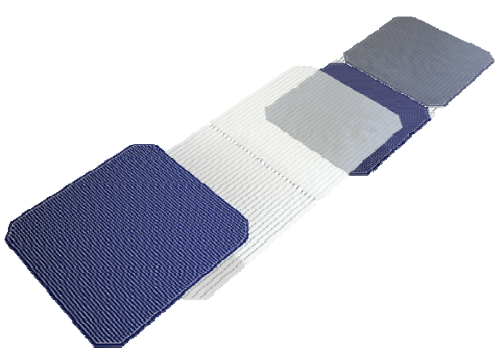

Figure 12: Concept of the automated SmartWire cell interconnection developed, enabling the direct interconnection with the wires of one cell front surface to the next cell back surface to produce SmartWire interconnected strings.

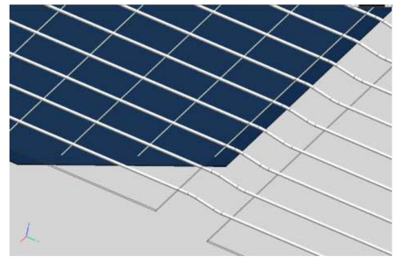

Figure 13: Close-up on flip-flop interconnection directly from one cell front surface to the next cell back surface.

3 R&D FOR SWCT COST REDUCTION

Further cost reduction of SWCT-HJT modules can be realized, first by changing the coating composition to reduce Indium use, and then by lowering the Ag in the cell metallization. Preliminary results are detailed for both developments in this section.

3.1 ALTERNATIVE WIRE COATING

A BiSn alloy coating was developed and tested to replace the InSn low melting point alloy coated on the SWCT wires surface. The objective is to reduce the wire coating cost, the main advantage of BiSn being its lower cost compared to InSn: Indium has a price similar to silver, while bismuth price is similar to that of tin. Bismuth-tin alloys are therefore about 20 to 70 times more competitive in costs compared to indium-based alloys.

A typical BiSn eutectic coating contains 58 wt% Bi and 42 wt% Sn, it has a melting point of 138 °C, a bulk resistivity twice higher than InSn alloy, and a coefficient of thermal expansion close to pure copper [7]. The cross-section observation of a BiSn coated copper wire in contact to a cell metallic back surface is shown in Figure 14 (in this example on an Al back surface field). The BiSn microstructure is shown in Figure 14b, with white contrast regions corresponding to an almost pure Bi phase (with < 5 %wt of Sn), and the darker regions in the coating corresponding to a Sn phase which can contain up to 20 %wt of Bi.

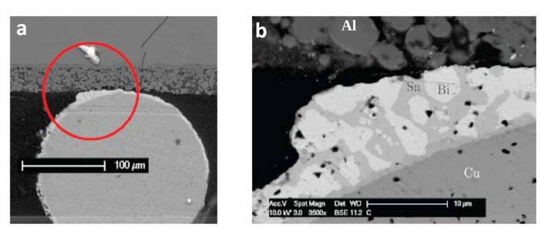

Figure 14: SEM image of the cross-section of the BiSn coated copper wire in contact to Al BSF. The BiSn coating microstructure is evidenced in the right image, with almost pure Bi phase and Sn phase with up to 20 %wt Bi.

Glass-glass SWCT-SHJ modules were produced using 38 wires with a 200 μm diameter and a BiSn coating instead of an InSn coating. These modules passed IEC tests with relative power degradation of -3.7 % after 200TC and -1.9 % after 1000 h DH, demonstrating that BiSn is a promising candidate for replacement of InSn. This result is further confirmed by a Gen4 module combining larger wires (18 wires of 300 μm diameter) with the use of BiSn wire coating, which demonstrates higher performance (see Table 5), and confirmed reliability with -2.7 % relative power loss after 200TC.

Name	***Voc (V)***	***Isc (mA)***	***FF (%)***	*Power (W)*
BiSn 200 μm	11.65	9352	75.2	81.94
BiSn 300 μm	11.61	9408	77.1	84.22

Table 5: IV-curve parameter from 16 cells module interconnected with 18 wires of 200 and 300 μm diameter and coated with BiSn.

3.2 SHJ CELLS WITH LOW SILVER CONTENT

The SWCT enables to use fingers with line resistance up to 10 Ω/cm [12], so that it allows implementing fine-line printed fingers. The challenge is therefore shifting from making high aspect-ratio's fingers to printing continuous finger as fine as possible to reduce the silver laydown (cost reduction) and increase the current density (efficiency enhancement). In our developments, a limit is now set by the minimum screen openings we could test, i.e. not lower than 20 μm. After 15 prints of low temperature silver paste, with a screen opening of 20 μm, we printed lines with 4 Ω/cm, with an homogeneous thickness of 6.0 ± 1.9 μm and a spreading of 32 ± 3 μm (see Figure 15).

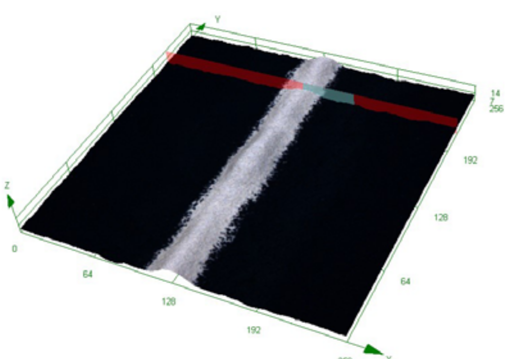

Figure 15: 3D reconstruction using a laser scanning confocal microscope (Olympus LEXT) of a low temperature silver paste printed with a 20 μm screen opening.

Bifacial SHJ cells were produced targeting minimum total Ag consumption in the front and back fingers. SHJ cell precursors produced by CIC were used. After optimizing the screen parameter (mesh count, wire diameter, emulsion thickness and line opening), the paste type, the grid design (number of finger) and the print parameters (speed, pressure, snap-off and squeegee), the number of fingers in front and in the back and the screen opening were fixed to 77 and 30 μm, respectively. The best cell efficiency was 22.2 % (see Table 6 for the other parameters) and the silver laydown was kept really low with only 15 mg per sides. This means the cost of silver is only 0.3 €ct/Wp for this bifacial SHJ cell.

	Mean	*best*
eff (%)	21.91 ± 0.23	22.18
FF (%)	77.00 ± 0.47	77.58
Isc (A)	9.45 ± 0.03	9.48
Voc (V)	0.732 ± 0.002	0.734

Table 6: IV-curve parameter from heterojunction (SHJ) c-Si solar cells with print laydown optimized to 15 mg per side (measured with the GridTouch®).

Such bifacial cells implementing only 30 mg in total of Ag in its front and back finger metallization were implemented in test mini-modules using SmartWire interconnection, demonstrating high performance, with a V_{OC} maintained at 730 mV, a fill factor of 74.4 %, and a short circuit current 9.302 A, for an aperture area efficiency of 20.8 %.

4 CONCLUSION

The SmartWire Connection Technology (SWCT) provides key advantages over standard busbar-ribbon technology for cell interconnections: low temperature contacting during module lamination, increase in efficiency by lowering ohmic losses and enabling fine-line printing, reduced consumption of silver by 85% or more on cell metallization, enhancement of module reliability (more than 1000 electrical contact points on each cell), and improved aesthetics. The SWCT was shown to be a key enabling technology for competitive silicon heterojunction modules, as it permits to lower the constraints on cell metallization conductivity. The high performance potential combining SWCT and SHJ cells is demonstrated with a certified 327 Wp module. In addition, prospects for ultra-low Ag usage were shown with bifacial SHJ cells implementing solely 15 mg of Ag per cell side. High reliability is confirmed with < 5 % degradation for up to 4000 hours of damp heat and 800 thermo-cycling tests for SWCT-SHJ 60 cells modules. Further cost reduction potential is demonstrated with first results of replacement of the state-of-the-art InSn wire coating by a BiSn alloy. Finally, outdoor bifacial module results have shown 15% more energy yield compared to a multi reference module and therefore demonstrates the full benefits for the end user of the GG-SWCT-SHJ technology.

5 AKNOWLEDGEMENTS

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6 REFERENCES

[1] T. Söderström *et al.,* Proceedings of the 28th EU-PVSEC, Paris (2013), pp. 495-499.
[2] A. Schneider, Rubin L, Rubin G. *Solar cell improvement by new metallization techniques - The DAY4™ electrode concept.* Proceedings of the 4th WCPEC, Waikoloa (2006), p. 1095.
[3] P. Papet et al., *Front grid metallization and module interconnections of industrial heterojunction solar cells,* Metallization Workshop, Konstanz (2013).
[4] S. Braun, G. Micard, G. Hahn, *Solar cell improvement by using a multi busbar design as front electrode, Energy Procedia* 2013;**21**:227-33.
[5] A. Mette, *New Concepts for Front Side Metallization of Industrial Silicon Solar Cells,* PhD Thesis, 2007.
[6] Press release, *Panasonic HIT® Solar Cell Achieves World's Highest Energy Conversion Efficiency of 25.6% at Research Level*, April 10, 2014, http://panasonic.co.jp/
[7] J. Glazer, *Metallurgy of low temperature Pb-free solders for electronic assembly, International Materials Reviews,* 1995;**40**,2:65-93.
[8] G. Cattaneo et al, *Encapsulants characterization for novel photovoltaic module design*, Proceedings of the 29th EU-PVSEC, Amsterdam (2014).
[9] S. De Wolf, *High Efficiency Silicon Heterojunction Solar Cells: A Review*, Green Vol. 2, pp. 7–24, 2012.
[10] M. Edward et al., *High Efficiency with Almost no metallization: multiple busbar wire interconnection of plated solar cells*, Proceedings of the 28th EU-PVSEC, Paris (2013), pp. 2097-2102.
[11] E. Kobayashi and Y. Watabe, *Rear-emitter Silicon Heterojunction Solar Cells with Cerium Oxide-Doped Indium Oxide,* Proceedings of the 29th EU-PVSEC, Amsterdam (2014).
[12] P. Papet *et al.*, *Metallization Skims Dedicated to Smart Wire Contacting Technology for Heterojunction Solar Cells*, Proceedings of the 29th EU-PVSEC, Amsterdam (2014).