SmartWire Connection Technology

T. Söderström[a], P. Papet[b], J. Ufheil[c]
[a] Meyer Burger AG, Schorenstrasse 39, CH-3645 Gwatt, Switzerland
[b] Roth & Rau Research, Maladière 23, CH-2000 Neuchâtel, Switzerland
[c] Somont, Im Brunnenfeld 8D-79224 Umkirch, Germany

*email: thomas.soederstroem@meyerburger.com, Phone : +41 33 221 23 88

ABSTRACT: For more than five decades, photovoltaic technology has seen continuous improvements, as costs have been consistently lowered, processes have been simplified and temperatures lowered. While significant improvements have been made at the cell level, limitations remain at the module level or at the interface between the cell and the module, which is known as the cell metallization-interconnection. Meyer Burger develops the Smart Wire Connection Technology (SWCT) required to close this gap and get the highest possible benefit out of high-efficiency solar cell performance. SWCT technology implies a change of paradigm. It requires the combination of lamination and interconnection into a single lamination step. Moreover, the module's silver paste consumption can be significantly reduced (< 2.4g/60 cells module) and even eliminated when Cu plating is used. There are also fewer electrical and optical losses thanks to the shorter length of the fingers and better light in-coupling than standard ribbon technologies.
Keywords: solar module technology, heterojunction, crystalline silicone, smart wire, connection

1 Introduction

Meyer Burger develops solar technology - from wafers to solar PV systems - with the aim of promoting the widespread use of photovoltaics energy and making solar power a first-choice source of renewable energy. To this end, the company focuses strongly on developing robust solar technology that is highly efficient, long lasting, and reliable. For the past twenty years, the topic of the interface between the cell and the module has been largely ignored. Today, high-efficiency solar cells such as heterojunction technology (HJT) (with efficiency exceeding 24.7%, as demonstrated in 2013 by Panasonic), the selective emitter, rear passivated cells, or interdigitated back-contact technology (IBC) require special care, as the loss during photo-generated current transportation should be reduced without sacrificing solar module reliability. Meyer Burger develops the wire bonding technology, known as Smart Wire Connection Technology (SWCT), with the aim of transforming high-efficiency solar cells into reliable modules while minimizing cell-to-module loss and cost. The technology transform the appearance of the front cell surface as presented in Figure 1 and offers additionally several benefits:

- By bonding multiple wires, ohmic losses and/or finger thickness can be limited, as the number of wires can be adapted to the specific cell's design
- Since busbars and the back side Ag screen are not used in this process, silver paste consumption can be significantly reduced
- As a result of the wires' smart light reflection, light coupling into the module can be improved when SWCT is applied
- SWCT reduces the impact of cell breakage by increasing the number of current collection pathways
- The process steps are simplified as the soldering and the lamination processes are coupled
- The technology reduces stress on the wafer, as the temperature during the connection process step is homogenous and kept below 160 °C
- Total cost of ownership is lower as a result of silver paste content of less than 2.4 grams per module with screen printed technology or even without silver used for Cu plating technology

SWCT is compatible with multiple material types such as Al, Cu, Ni, Ag and therefore opens the door to new material combinations and the interconnection of new cell concepts, such as rear passivated cells, HJT, metal plating and IBC.

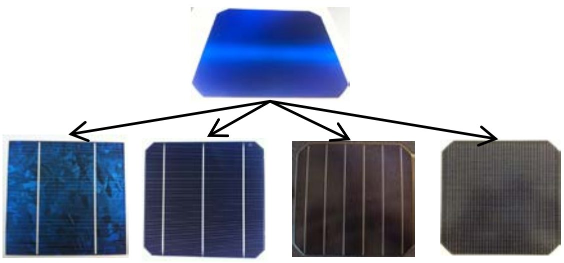


Figure 1: Evolution of cell front side appearance from 2 BB to SWCT.

2 SWCT working principle

SWCT is a contacting cell technology based on wire bonding. Typically, between 15 and 38 wires are used on both sides of the solar cell. The wires are round copper-based wires coated with a low melting-point alloy, generally a layer of 1-2 microns in thickness with 50% indium alloy (Figure 2). The wires are embedded in a polymer foil that is applied directly onto the metallized cell (Figure 3). The stack is then laminated together. The wires are then bound to the metallization of the cell and provide electrical contact to most of the material (e.g. Cu, Ag, Al, Ni, and their alloys). The number of wires and their thickness can be customized to match almost any cell metallization design or cell power class. It should be noted that busbars on the cell surface (both on the front and back side) are not needed. This will save material costs (especially if the metallization scheme required expe

nsive material, such as silver paste) and prevent unnecessary shading. SWCT has the added benefit that better cell backside passivation can be achieved with either a full-face aluminum screen printed back surface field, or with any novel backside passivation concept (such as SiO, a-Si, AlOx, etc.). This is because high-temperature soldering steps can be avoided and the constraint between the wire and metallization relaxed.

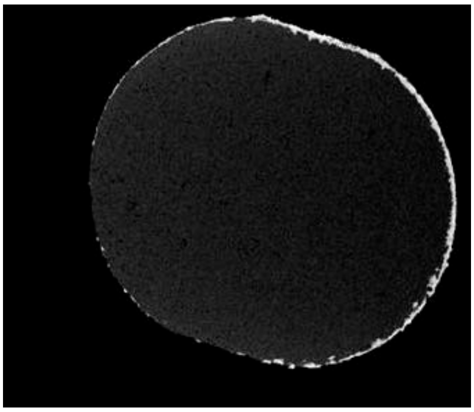


Figure 2: Left: SEM cross-section of a 200-micron thick Cu wire coated with an indium alloy.

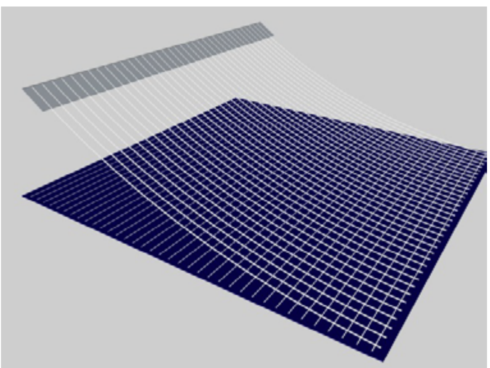


Figure 3: Left, the electrode being applied to the cell metallization. Right, one-cell mini-module connected with SWCT.

3 Module efficiency

Achieving the highest possible level of efficiency out of a given solar cell power class is the ultimate aim of solar module technology. However, the cells are brittle and therefore need to be protected to resist outdoor conditions such as rain, hail, damp, wind and snow last. The protection is usually achieved by embedding the cell in a glass and an encapsulation layer. This gives rise to optical losses compared with the cell measurement procedures such as light reflection and transmission loss. In addition, since the photo-generated current needs to be transported from one cell to the other and then out of the module, electrical losses occur. The most reliable, proven and common techniques used today is ribbon soldering. Here, we will point a few of the SWCT advantages compared to this mainstream technology.

3.1 Electrical loss in solar modules

The front side of conventional crystalline silicon solar cells has fingers and bus bars. Fingers collect current uniformity generated on the cell surface to the bus bars. From these bus bars, current flows to copper ribbon that is soldered up to each bus bar. These ribbons make it possible to transport the photo-generated current out of the solar cell area to the next solar cells. This, in turn, forms a string and the strings form a module. A decade ago, all PV modules were built with solar cells containing two bus bars on the front side. Today, however, most PV modules are based on three-bus bar solar cell design. This evolution has been driven mainly by cell efficiency, which is higher with three bus bars than with two. In fact, by using three bus bars, finger length is reduced from 52 mm to 39 mm as shown in Table 1 and therefore less current is collected per individual finger. Ohmic power loss per finger drops and more power can be extracted from each individual solar cell. The evolution to SWCT is driven by the same idea; namely, that reducing the finger's length decreases its ohmic dissipation and extracts more power per solar cell. In fact, instead of three copper ribbons, SWCT technology offers up to 38 coated copper wires that carry the photo-generated current outside the cell area. Finger length can be decreased from 39 mm (3 bus bar cells) to 4-8 millimeters, which in turn makes a finger's ohmic power losses negligible. This reduction of finger length is obtained without sacrificing in the crossection of the material transporting the current out of the solar cell. Table 1 shows that SWCT with 30 wires of 0.2 mm in diameter has the same optical shading compared to 3BB but a superior Cu crossection (0.94 mm2 compared to 0.68 mm2) but still a reduced finger length (5mm compared to 39 mm). Table 1 shows as well that SWCT with 18 wires of 0.3 mm of diameter has 85% higher Cu crossection compared to 3BB, a reduced optical shading (2.6% compared to 2.9% for 3BB) and the additional benefits of reduced finger length (8.2mm compared to 39 mm for 3BB). In conclusion, this Table 1 demonstrates that SWCT is showing better properties than ribbon technology.

Table 1: Comparison of the dimension of ribbon and wires technologies. The optical shading is calculated as the ratio between the width of the ribbon/wire and the cell length . For SWCT, this number is corrected with a 75% effective optical shading as discussed in section 3.2

Contact-ing scheme	Wire diam-eter [mm]	width [mm]	Crosse ction [mm2]	Finger length [mm]	Optical Shading [%]
2 ribbons		4	0.60	52.0	2.6%
3 ribbons		**4.5**	**0.68**	**39.0**	**2.9%**
5 ribbons		5	0.75	26.0	3.2%
6 wires	0.2	1.2	0.19	22.3	0.6%
12 wires	0.2	2.4	0.38	12.0	1.2%
18 wires	**0.2**	**3.6**	**0.57**	**8.2**	**1.7%**
22 wires	0.2	4	0.69	6.8	1.9%
30 wires	**0.2**	**6**	**0.94**	**5.0**	**2.9%**
38 wires	0.2	7.6	1.19	4.0	3.7%
18 wires	**0.3**	**5.4**	**1.27**	**8.2**	**2.6%**

In order to assess the potential of the SWCT and demonstrates the electrical gain (FF gain) compared to ribbon technology; we prepare 1 and 2 cells modules with cells screen printed with and without BB. The idea here is to have the same intial cell and adjusting the metallization for ribbons or SWCT. Two type of cells are presented, a monocrystallline high temperature diffused cell from our partner Hareon solar in China and a HJT cell from our R&D pilot line in Switzerland (Neuchâtel). Both cells are then screen printed with bus bars (BB) at the front side and no BB at the back side. Avoiding BB at the back side reduced the metallization cost and improves the back side passivation for the diffused cells. Figure 4 collects the module efficiency data of the mono c-Si cell. The cells were made identical before the metallization step. Then, a group was screen printed with 3 BB, a group with 5BB and a group with only finger (0BB). Then the group with 3 and 5 BB was connected with ribbon and the group without BB was connected with SWCT. Each minimodule is then build with 2 cells connected in series.

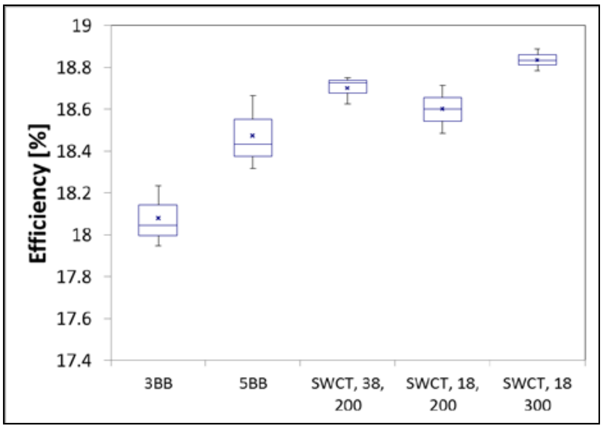


Figure 4: Module efficiency of the mono cells connected with 3 and 5 ribbons and the same cells connected with SWCT of 38 and 18 wires with 200 mu wire thickness and 18 wires with 300 mu wire thickness.

Table 2 collects the data of module prepared with high temperature mono cells and a HJT cells. The SWCT has a relative FF gain of respectively, 3.7%, and 5.1 %, for the high temperature and HJT solar modules connected with 38 wires compared to the same cell but interconnected with ribbons. This loss is shared between the front and the back side of the solar cell and is proportional to the square value of the current. Thickening the ribbon, would reduce the loss in the 3 and 5 BB ribbon as demonstrated by Qi et al [1]. However, doing this is not advisable, as it requires more encapsulant during module production, i.e. more cost, and puts the solar cells under greater stress and therefore increased the risk of breakage rate by a factor 2 as discussed by Qi et al [1]. SWCT actually reduces electrical losses both in the fingers and along the wires. In conclusion, SWCT can reduce the electrical loss resulting from the interconnection as shown here and this was also previously reported shown in the past in [2,4]. The trade-off between shadowing and electrical loss must always be optimized for each cell design, as this makes it possible to evaluate the potential of SWCT for a given technology. This studies demonstrates the lower electrical losses of the SWCT compared to a standard 3 ribbon technology can be achieved and is transformed into an efficiency gain of respectively, 4.2% and 5.7 %, for a diffused and HJT solar module technologies. The gain is higher for the HJT cell compared to the high temperature cell since a low temperature paste is used for the HJT cell. This low temperature paste has a reduced conductivity as discussed in section 3.3 and therefore the advantage of SWCT is in this case even more important.

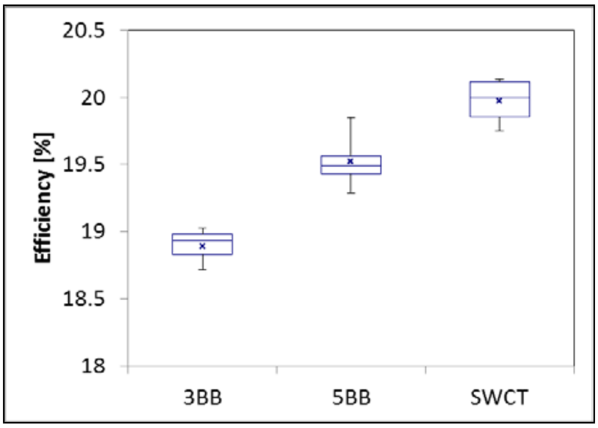


Figure 5 : Module efficiency of the HJT cells connected with 3 and 5 ribbons and the same cells connected with SWCT of 38 wires with 200 mu wire thickness.

Table 2: The electrical performance of mono and HJT c-Si solar cells connected with 3, 5 ribbons and SWCT. The 3BB cells are interconnected with ribbon (0.15 mm * 1.5 mm), the 5BB with 5 ribbons (0.2mm*100) and the bus bar less cells are connected with SWCT (x wires of 0.2 and 0.3 mm diameter). The efficiency gain is always compared to the 3BB reference cell.

Module with mono c-Si cells from Hareon Solar china

	BB	wire	wire thick-ness [mm]	Eff. [%]	J_{sc} [mA]	FF [%]
Ribbon ref	3			18.08	9.15	75.47
Ribbon	5			18.47	9.12	77.13
Eff. gain [%]				**2.2**	**-0.3**	**2.2**
SWCT	0	38	0.2	18.70	9.04	78.37
Eff. gain [%]				**3.4**	**-1.2**	**3.7**
SWCT	0	18	0.2	18.60	9.25	76.2
Eff. gain [%]				**2.9**	**1.1**	**1.0**
SWCT	0	18	0.3	18.84	9.15	78.00
Eff. gain [%]				**4.2**	**0.0**	**3.2**

Module with Mono HJT c-Si cells from Meyer Burger

	BB	wire	wire thick-ness [mm]	Eff.[%]	J_{sc}[mA	FF [%]
Ribbon	3	0	0	18.89	8.90	71.1
Ribbon	5	0	0	19.52	8.90	73.58
Eff. gain [%]				**3.3**	**0.0**	**3.5**
SWCT	0	38	0.2	19.97	8.91	74.95
Eff. gain [%]				**5.8**	**0.1**	**5.1**

3.2 Optical shading

Optical losses in the module are typically the result of light shading, light absorption in inactive layers and light reflection. SWCT reduces shading by avoiding the use of bus bars on the cell. Bus bar shading is typically 2.9% for a solar cell with 3BB design with a 1.5 mm-wide busbar. Thanks to the geometry of the round wire used in Smart Wire technology, this shading can be reduced to a lower level with SWCT than with ribbon technology. This concept was already presented by Braun et al. [4] and it is reproduced here in Figure 6. The wire geometry allows the light to be reflected either back to the glass, where internal reflection occurs when the angle of incidence is above 42° or directly toward the solar cell. Table 3 collects the IV data of a HJT cells without bus bars and connected with a varying number of wires in a module. Effective shading of 151 microns for a 200 micron-thick wire is found and presented Table 3. Here, only 75% of the wire diameter affects the shading. This beneficial effect is the result of the light reflection on the round wire surface, which is then trapped in the module as described in Figure 5. The experimental data also supports the early simulation of Braun et al. [4], which foresaw a shading potential up to 30% for round wire. In conclusion, shading was reduced by 25% compared ribbon technology with upward potential. Indeed, the wire geometry and the wire reflectivity could be further improved. Our simulation (not shown here) suggests that the shading can be reduced below 10% with an optimized design. This potential will be further investigated in the future.

Table 3: Electrical performances of HJT solar cells connected with 6, 18 and 36 wires of 200 microns in diameter. Shading diameter is calculated from the linear interpolation of J_{sc} variation with the equation 1 where x is the number of wire, I_0 is the J_{sc} without shading, I_x the J_{sc} with x wires and d the shading diameter.

$$I_x = I_0 * (1 - \frac{x*d*156}{243})$$

Equation 1: $I_x = I_0 * (1 - \frac{x*d*156}{243})$

wire number	6	18	36
Eff. [%]	18.17	19.09	19.1
Isc[A]	8.94	8.84	8.68
FF [%]	68.21	72.68	74.24
Shading diameter [mu]	155	148	151
Total shading	0.60%	1.70%	3.50%
Crossection [mm2]	0.19	0.57	1.13
Finger length [mm]	22.29	8.21	4.22

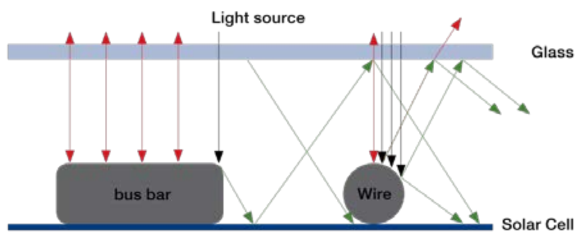


Figure 6: Light reflection on solar module connected with ribbon,

round wire shape. The round shape of the wire introduces a light trapping effect which reduces the shading of the wire by 25%.

3.3 Metallization

SWCT improves the cell interconnection by reducing the finger length and shading. The defining potential of SWCT is in the direction of new metallization designs and schemes. Indeed, silver paste metallization consumption is a key parameter in order to reduce the cost of the solar module. 200 mg of silver paste consumption per cell represents 12 g/module and thus 3.7 c$/Wp for a 300 W module with a silver price of 925 $/kg. This means that production costs can be reduced if bus bars are avoided and finer printed lines used or if silver is replaced with a low cost material. To achieve this, narrower finger lines or other metallization schemes are needed and the following experiment illustrates this point. The performances of HJT solar modules made with identical solar cells but different metallization are presented in Figure 7. These solar cells were either screen printed with three different screens or plated with Cu. Screen A was made of 3 bus bars (1.5 mm) and 70 fingers between 90-100 µm in width, i.e. 350 mg of Ag paste for a 6-inch solar cell. Screen B formed 70 fingers between 90-100 µm in width, i.e. 110 mg of Ag paste for a 6-inch solar cell. Screen C formed 70 fingers between 60-70 µm in width, i.e. 40 mg of Ag paste for a 6-inch solar cell. Option D formed 70 Cu plated fingers between 50-60 µm in width, i.e. 0 mg of Ag paste for a 6-inch solar cell. Finger resistance was 0.6 Ohm/cm for screen A and B, and 2 Ohm/cm for screen C. Screen A was connected with 3 ribbon and the others interconnected with SWCT.

Figure 7 shows that SWCT enabled a reduction in Ag consumption of 21 g/module (350 mg/cell) and this corresponds to a relative increase in module efficiency of 5.7% over the cell with bus bars and connected with ribbons. The absence of bus bars in screen B, the finer lines of screen C and option D resulted in this gain. The fingers were shorter due to SWCT and therefore finger power losses were negligible with screen C. In contrast, a three-bus bar design combined with 2 Ohm/cm fingers (as used in screen C) would lead to poor cell performance due to a high level of power dissipation in the fingers. Thanks to SWCT technology, fine-line printing led to better module performance and constrained on-finger conductivity was relaxed compared with conventional ribbon technology. Our simulation indicated that finger resistance up to 100 Ohm/cm could be combined with SWCT without significant power losses. This key advantage gives rise to new opportunities for fine printing technologies, such as aerosol jet, ink jet, offset printing, plating, dispensing or extrusion.

As presented in the experiment above, fine-line printing and Cu plating improve solar module efficiency and also reduces or eliminates Ag paste consumption. The results presented here are for HJT cells here but is also very weel adapted to screen printed multicrystalline cell and plated monocrystalline cells. Indeed, Edwards et al [8], reported a gain of 3% in efficiency for a multicrystalline cell with a silver metallization of only 65 mg compared to a 3BB cell connected with ribbon and a plated monocell with almost no metal, i.e. only 1 micron of Ni fingers and a FF over 74% at the module level.

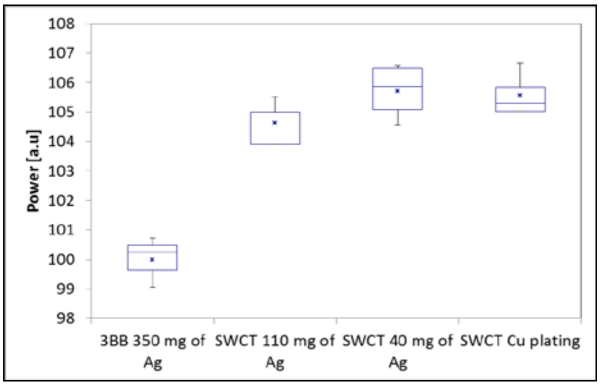
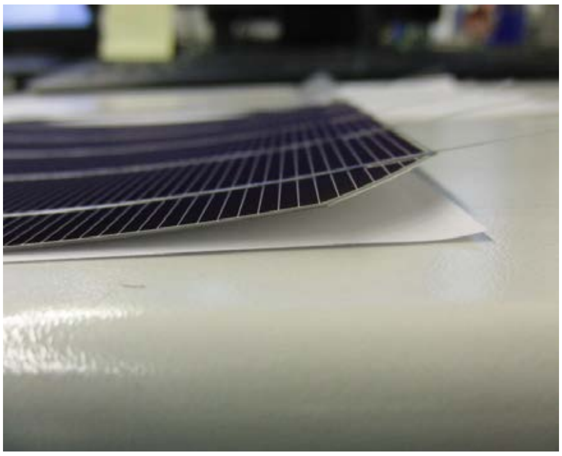


Figure 7: HJT solar cells were screen-printed with three different screens on the cell's front side. Screen A formed 3 busbars (BB) of 1.5 mm in width and 70 fingers ranging from 90-100 mu in width. Screen B formed 70 fingers ranging from 90-100 □m in width and Screen C formed 70 fingers ranging from 50-60 □m in width. Option D formed 70 Cu plated fingers ranging from 50-60 □m in width. The cells metallize with screen A are soldered with ribbon and the remaining cells were laminated into one cell module with SWCT .

4 Cell stress

The cells experiences some stress during its fabrication and the module process. In the extreme case, this causes cracks and/or cell breakage. The reasons behind cell breakage in a module are complex. While it can happen at any point between ingot growth and lamination, breakage can be avoided if appropriate wafer material is selected and stress on the wafer is reduced throughout the process. SWCT exerts less stress on the wafer than standard soldering technologies thanks to the reduced temperature process (<160°C) and the flexibility of the multiple thin 200-micron wires as opposed to the three stiffer ribbons of 1-2 mm in width.. The curvature of cell after interconnection is an excellent signature of this stress as shown in Figure 8 where the same monocrystalline cell was interconnected with ribbon and SWCT.



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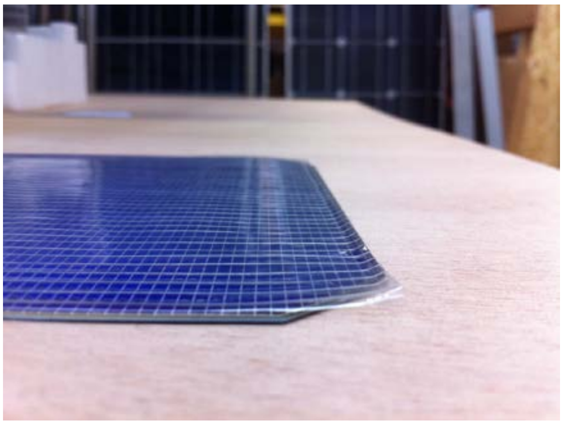
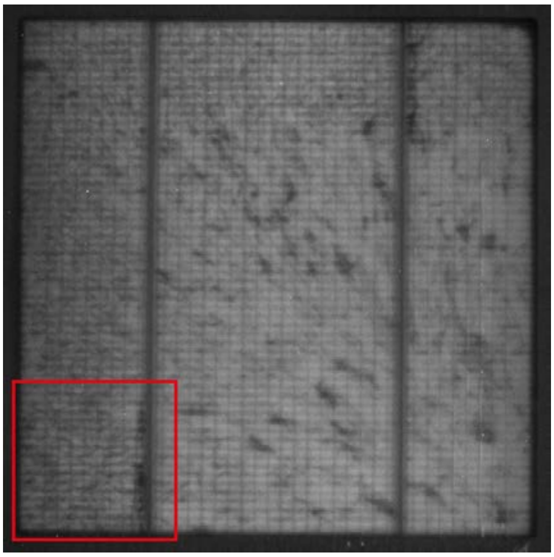


B

Figure 8: Two pictures of cell interconnected with ribbon (A) and soldering (B).

In the unfortunate event of cell breakage, SWCT can decrease this potential negative effect. Earlier studies, such as that of Sander et al. [5], showed that ribbon interconnections were at the root of cracks and that cracks parallel to the ribbon would keep the cell inactive. Cell breakage is reproduced here in Figure 9 to illustrate the behavior of SWCT compared to ribbon technology. Two cells were deliberately broken in a similar procedure along the length of the bus bar (red square). One cell was interconnected with SWCT and the other cell was soldered with two ribbons. This experiment demonstrated that the cells connected with SWCT were still completely active, even though the cell was broken. In contrast, the cell connected with ribbons had a completely inactive area (dark area in red square).



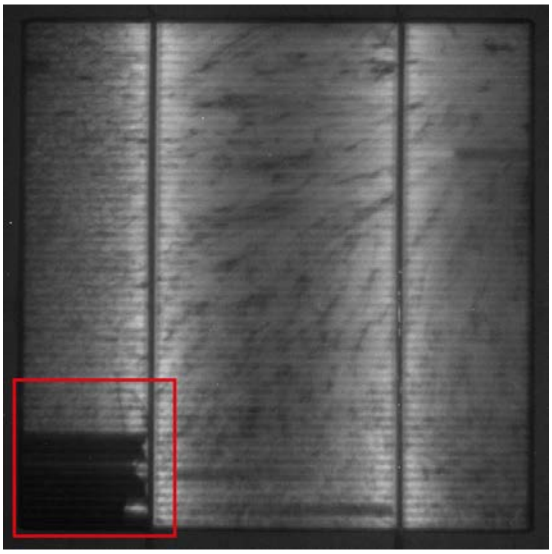


Figure 9: Left and right: EL image of a one-cell module interconnected with SWCT and soldered ribbons. Both cells were deliberately broken in the area within the red square (along the busbar).

6 Module reliability

The reliability and outdoor performance of a PV module is one of the end user's biggest concerns because the investment is a medium to long term investment and therefore has to last over the years. Even the highest-efficiency module needs to last 20 to 40 years in outdoor conditions. Here, extended climatic chamber tests required for IEC certification, damp heat (DH, 85%, 85°C) and thermo cycling (-40° to 80 ° in 6 hours) are presented. Damp heat is critical for the encapsulation material and the cell technology, whereas thermo cycling is vital when it comes to the reliability of interconnection technology.

6.1 Encapsulation

Standard module design comprises an EVA encapsulation layer and a PET-based back sheet. This sandwich has the disadvantage of degradation when modules are exposed to moisture. This effect is shown in Figure 10, where power loss data from solar modules made with standard c-Si cells and encapsulated with materials such as TPU, TPO and EVA were collected. The cells are diffused cells used in our module production in Switzerland (Thun). A strong power loss in damp heat conditions for a module with EVA was observed. This power degradation between 2000 and 6000 hours of DH for modules encapsulated with EVA material is classic, as shown in the following publications [6, 7].The EVA grade is usually the main criterion for the timing of the degradation. The superior performance of liquid silicon and TPO compared with EVA is shown in Figure 10. The liquid silicon and TPO encapsulant absorbed less moisture than EVA. Both of these materials offer protection against potential induced degradation (PID), as described in [6]. TPO has been chosen as the current solution for SWCT as it provides a more reliable performance and is available as a foil at a low cost.

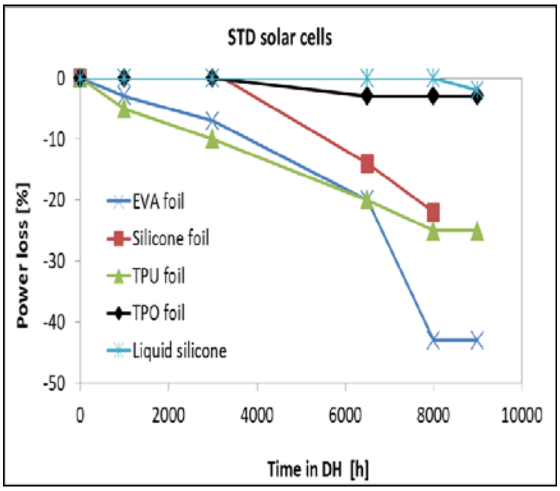


Figure 10: Mini-module performance following damp heat exposure. The modules were encapsulated with various materials and the cells standard c-Si cells metallized with a high-temperature silver-based paste.

6.2 Connection Technology

The critical test for the interconnection technology is the thermo-cycling test. Figure 11 presents the results of mini-modules based on HJT and standard cells that were connected with various technologies. SWCT provided excellent resistance to thermo-cycling test conditions, as no power degradation was observed on HJT modules following more than 800 cycles (four times the IEC criteria). This clearly demonstrates the superior performance of SWCT compared to other connecting technologies for this low-temperature, silver-paste metallization scheme. SWCT provide also excellent durability for standard cell with up to 400 cycles without losses. The modules will remain in the chamber until a failure appears.

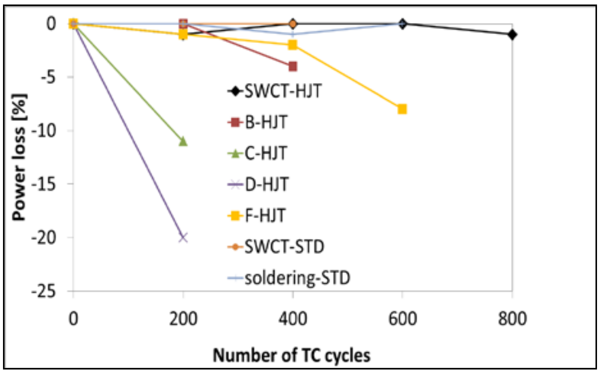


Figure 11: Performance loss of SWCT modules after thermo-cycling aging compared to other connection technologies. Both HJT and standard (STD) c-Si cell are presented here.

7 Conclusion

SWCT is a breakthrough connecting technology that is compatible with most of the cell technologies available today and provide long term durability. It is especially attractive for next high-efficiency solar cell technologies because it can minimize current collection losses, can be connected to various metals and alloys and Ag consumption can be extremely minimized. This short paper demonstrates that SWCT reduces the shading loss by 25% and increase the module efficiency by up to 5.7% thanks to the removal of bus bars and the use of finer finger lines. The decreased use of silver paste is also shown here and this reduces costs by to 4-6 US$cts/Wp depending on the initial paste consumption. The results presented herein demonstrate that the Ag paste consumption can be reduced by up to 2.4 g/module with conventional screen-printing technology. Moreover, SWCT opens the door to a wide range of applications because the bonding works with a wide variety of metals and semiconductors.

8 Acknowledgements

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