INTERCONNECTION 1, 2, 3, 4.0:
BUILDUP TOWARDS A PV TECHNOLOGY HERO?

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Topic 1.2 New Materials and Concepts for Cells and Modules

New cell materials and concepts e.g. use of nanotechnologies and quantum effects. New module materials and concepts.

BACKGROUND: MERGING CELL AND MODULE DESIGN

In the field of c-Si PV interconnection, interest in more efficient interconnection technologies with high aesthetical value is steadily growing, to catch up with the impressive efficiency progress at cell level during the last years, now nearing the fundamental limits for cells based on crystalline Si as absorber [1].

This interest is being translated in an increasing number of busbars for cell interconnection, culminating in the introduction of multi-wire interconnection technologies [2]. With such an approach, the optical performance is improved by reducing effective shading area and the generated electrons are extracted more efficiently out of the cell. This relaxes the requirements for the cell metallization and cell doping and results in reduced electrical losses and/or metallization cost. To get the most out of such an approach, the cell (metallization) and interconnect scheme should be meticulously co-designed. As the production for such 2-side contacted (and bifacial) cells and interconnection technologies is rather close to the industry standard, it can be implemented relatively straightforward.

Next to this trend, a revival of (also bifacial) back-contacted cell technologies is seen, thanks to recent breakthroughs in efficiencies [3] and cost reductions in materials and process steps. Though further away from current industrial focus, the promising potential of such cells raises a need for efficient and cost-effective interconnection technology. Given the increased complexity for cell metallization compared to 2-side contacted cells (patterning and alignment steps), and higher process and material costs of metallization on cell level and cell insulation, there is an even greater interest to relax requirements on cell metallization level as much as possible and shift it to the interconnection level.

With an overview of our holistic approach in developing such interconnection technologies for both 2-side- and back-contacted cells, this abstract reports on their current state of development and describes how these developments symbiotically reinforce each other.

1.0: TABBING-STRINGING

At present, standard module production is based on tabbing and stringing of cells into cell strings. After the layup of the strings, they are then interconnected and laminated to create a module. Currently, the number of busbars has evolved to 5 per cell to reduce resistive losses and costs in the cell metal grid. An implementation of this is the Schmid multi-wire stringing approach [2], further improving light harvesting and reducing resistive interconnection losses and cell metallization. Meyer Burger went even further and introduced the Smart Wire Connection Technology [4], a technology that combines multiple wires with a polymer foil to create an interconnection sheet. These are pre-laminated on busbarless cells to form strings, and after lay-up are laminated into modules during which a low-temperature solder interconnection with the cell fingers is created.

2.0: MULTI-WIRE FOR 2-SIDE CONTACTING

As mentioned above, a multi-wire approach for 2-side contacted bifacial and busbarless cells allows a significantly improved trade-off between optical (finger shading) and electrical (resistive transport) losses, while the potential reduction in cell metallization is promising from a cost perspective, and the more uniform appearance allows a more aesthetical appeal. In this approach, we aim to combine interconnection and encapsulation, without using additional materials and avoiding a separate soldering or lamination process, by integrating the interconnection wiring directly into the encapsulant material [5]. To this end, we optimize the lamination process and material selection for optimal solder joint formation and encapsulation. As solder reflow and encapsulant melting are taking place simultaneously during lamination, rheological measurements are needed to reveal the encapsulant viscosities at various temperatures. SEM-EDX inspection of solder joints' cross-sections (Figure 1) and IV and EL measurements help with the assessment of the cell interconnection and allow to optimize the lamination process window.

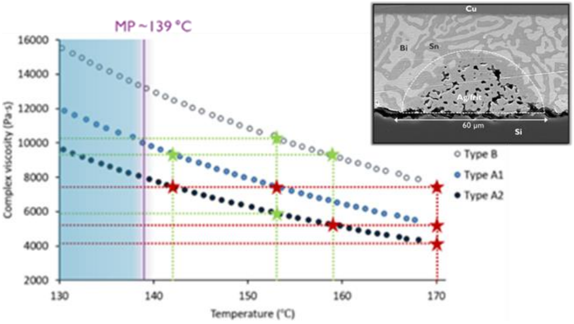

Figure 1: Encapsulant viscosity measurements and test matrix definition, cross-section of a solder joint

Based on such a preliminary optimization, we prepared 3x3 cell modules and compared them to standard 5BB tabbing-stringing and SWCT interconnection (Figure 2).

	STD 5BB	SWCT	TWILL
			
# Ribbons	5	18	20
Ribbon cross-section	0.22x0,9 mm²	∅ 0.3 mm	∅ 0.2 mm
Total cross-section (mm²)	0.99	1.27	0.63
I_{sc} [a]	9.51	9.24	9.67
Voc [mV/cell]	661	646	656
FF [%]	77.6	80.3	74.8
P_{mpp} [W/cell]	4.883	4.792	4.742

Figure 2: Comparison and electrical measurements of different interconnection technologies

Following up on this technology, we are developing a scalable production method for this technology, in first instance, targeting BIPV applications allowing highly customized but at the same time automated module fabrication. In a later stage, the technology has the potential to enable a further cost reduction even for mass manufacturing of standard PV modules. To this end, together with industrial partners we are developing approaches to integrate interconnect wires into encapsulant foils as well as the encapsulant material and the lamination process window. For the layup, we have acquired a flexible pilot tool that allows automated cell- and foil placement with sufficient alignment accuracy, shown in Figure 3 (though it can do much more, cf. next section).

Figure 3: Multi-functional automated module layup and interconnection tool

3.0: MULTI-WIRE FOR REAR-SIDE CONTACTING

Also, for back-contact cells, a multi-wire approach can be very interesting. In this case, the technology similarly allows an improved and interesting trade-off between electrical and financial implications, but this time more or less independent from optical considerations. Such an approach can be realized through an evolution of the solder-through technology [6], wherein the interconnection ribbons are replaced by wires and interwoven with the insulating glass fibre yarns to create a hybrid fabric (Figure 4) [7].

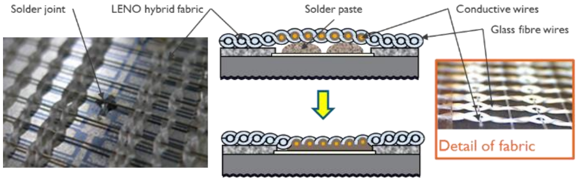

Figure 4 left to right: interconnected IBC cell, cross-section of interconnection principle, LENO fabric detail

Though there are interesting opportunities for performance optimization with this technology through using a tapered interconnection scheme, as illustrated in Figure 5, a thorough cell-module co-design is required to reach its full potential.

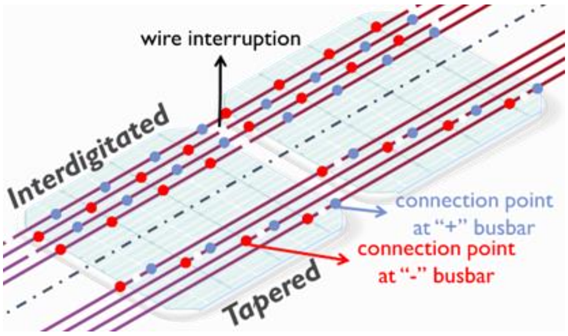

Figure 5: Interconnection scheme of hybrid woven multi-wire and glass fibre fabric BC-interconnection

In a concrete case, the occurrence of dissimilar current generation in IBC sub-cells (e.g. caused by unequal sub-cell sizes) may cause resistive and fill factor losses, as illustrated in Figure 6 [8]. Current redistribution paths on cell metallization or fabric level may avoid such pitfalls; this should be considered and tested in the design phase.

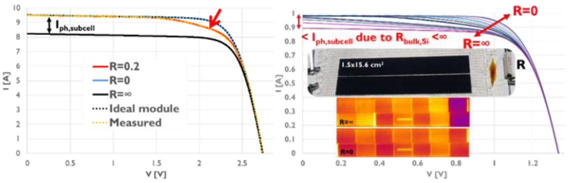

Figure 6: Influence of interconnection tapering on sub-cell non-uniformity and current redistribution

The technology itself is based on a monolithic fabrication approach from the glass up. Though initial interconnection experiments were based on manual fabrication (dispensing, alignment and soldering) of 1-cell and 4-cell IBC laminates using small fabrics [5], new development is ongoing to transfer the technology to an automated setup (Figure 7).

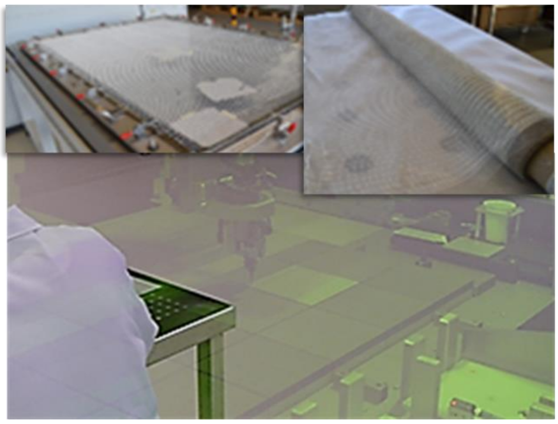

Figure 7 Various pictures of fabric, layup, automated paste dispensing

This tool, shown in Figure 3, enables the automatic placement and alignment of cells, dispensing of the conductive paste, alignment of the interconnection fabric, automatic hot-air soldering and laser-cutting of the conductive wires in the fabric. Industrial MWT cells have been designed and fabricated, as well as corresponding large-area fabrics, including also first trials to simultaneously integrate bussing wires. Promising results have been obtained in the tool meeting its specs, separate and combined process steps and first 1-cell laminate results (Figure 8). Further process development and upscaling efforts are ongoing.

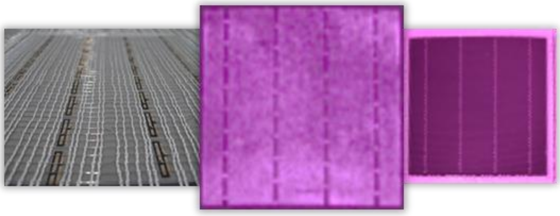

Figure 8: fabric-interconnected MWT cell, EL images (front- and backside)

INTERCONNECTION 4.0: SYMBIOSIS WITH ENCAPSULANT-INTEGRATED DISTRIBUTED RIBBONS

Building further on the above approaches, the next step is to combine the benefits and develop a combined interconnection and encapsulation process for back-contact cells through integrating the conductor into the encapsulant using a smart tapered design without additional materials or processes.

The backbone for this module-level interconnection technology somewhat resembles a flexible integrated backsheet printed circuit board (PCB), as in the conductive backsheet approach [9]. While PCB conductive layer patterning, insulation layers, conductive paste application and corresponding alignment steps add to the cost and limit the wider adoption of this conductive backsheet approach, our 3D-woven interconnection foil proposes a cost-effective alternative, by interweaving metal and encapsulant ribbons. The encapsulant ribbons provide encapsulation material and simultaneously ensure electrical insulation where needed. The metal ribbons in the weft direction will partially or fully replace the cells' busbar metallization and allow interconnection to the adjacent cells at the end of a cell string. The ribbons in the warp direction are consisting of a combined layer stack of an electrically insulating encapsulant and a metal ribbon. These warp ribbons will allow electrical connection to the adjacent cells within a cell string [10, 12].

Depending on the weave design, a specific ribbon interconnection pattern is created: when the weft ribbons are crossing over the combined warp ribbons, an electrical intra-weave contact is created between both warp and weft metal ribbons. When crossing under the warp ribbon an insulated crossing point is created due to the insulative properties of the encapsulant layer (Figure 9,10).

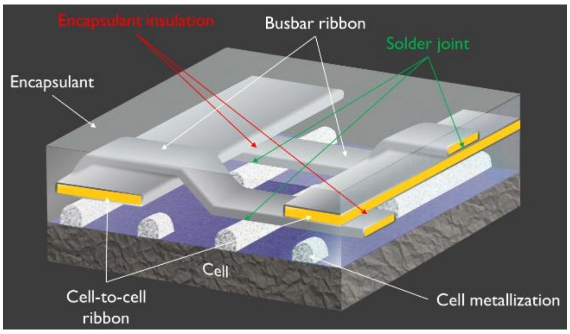

Figure 9: Cross-section drawing detail of 3D-interconnect after lamination

After weaving, the resulting weave can be used as a contact sheet for cell interconnection; Depending on the side where the warp or weft metal ribbons are exposed on the fabric surface with regards to the cell, they can be used for cell-to-cell interconnection (metal away from the cell) or as cell collection busbar (metal towards the cell) between the collection points (MWT) or fingers (IBC) of the cell. Local interruptions of the cell-to-cell busbars create a tapered design, determined by the weaving pattern. Each ribbon can thus be used for both polarities, optimizing the total copper usage and cost. The drawing below (Figure 10) illustrates the principle. Here again, an intricate cell-module co-design is required for the technology to reach its full potential.

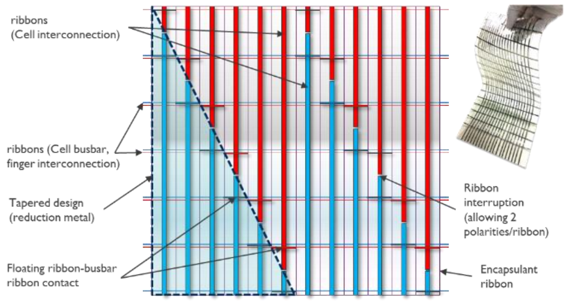

Figure 10 Left: fabric structure with tapering Right: prototype of a woven 3D interconnection sheet.

Also, here, first indications from technology development seem very promising [11]. In a preliminary demonstration, a fabric was prepared with a stacked combination of SnBi-coated Cu-ribbons and encapsulant ribbons in warp, and SnBi-coated Cu-wires for cell busbar interconnection in weft. The ribbons are then interrupted to create a tapered interconnection scheme.

The dummy IBC cell has 6 sub-cells and metallization only consists of interdigitated fingers. As the cell metallization busbars are replaced by the copper wires in the fabric that directly contact the cell fingers with similar polarity during lamination, no busbars are needed in the cell metallization, optimizing the active area of the (bifacial) cell. The front encapsulant, the dummy cell and the 3D fabric are aligned and laid up between 2 glass plates, after which the stack is laminated. No backside encapsulant is needed as this is already incorporated in the fabric (Figure 11), and just a single fabric lamination step is needed to simultaneously align insulator and contacts. During lamination, local solder contacts in the fabric and between fabric and cell are created.

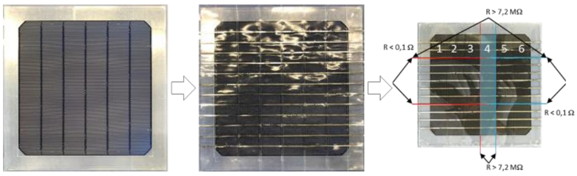

Figure 11 left: cell and contact sheet lay-up, Right: R-measurement after lamination

2-point resistive measurements indicate that there is no significant shunting between the polarities and good intra-fabric solder contacts between wires and ribbons.

A similar experiment is performed with an MWT cell in a single-cell laminate (Figure 12). In this case, SnBi-coated ribbons are used in warp and weft, with encapsulant ribbons combined with the metal ribbons in warp. Despite the limited performance of the MWT cell due to the specific backside design that was developed for multiple interconnection test purposes, and the unadjusted ribbon dimensions, electrical measurements revealed the proof-of-concept to be functional, with EL imaging indicating a very uniform interconnection.

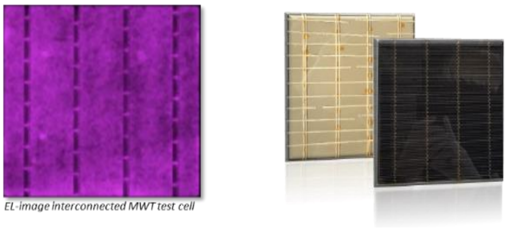

Figure 12 EL-, front- and backside image of 3D fabric interconnected MWT cell

CONCLUSION AND OUTLOOK

In this paper we report on several new interconnection technologies for bifacial and back-contacted (bifacial) cells, in different stages of their development. We discussed the relationship between the different technologies and their benefits that are ultimately combined into a new technology, suited for efficient interconnection of (bifacial) back-contact cells.

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REFERENCES

[1] ITRPV roadmap, 2016
[2] S. Braun et al., SiliconPV, 2013
[3] Kenji Yamamoto et al., EUPVSEC, 2017
[4] T. Söderström et al., EUPVSEC, 2013
[5] T. Borgers et al., IEEE PVSC, 2016
[6] Photovoltaics International Vol. 17 Sept. 2012
[7] EP2660878 (A1)
[8] J. Govaerts et al., EUPVSEC, 2017-2AO.5.1
[9] I.J. Bennett et al. EUPVSEC, 2014
[10] EP3258503 (A1)
[11] R. Van Dyck et al., SiPV, 2019 (accepted for presentation)
[12] J. Kroon et al., Photovoltaics International 2018, Vol. 41