3-Dimensional Multi-Ribbon Interconnection for Back-Contact Solar Cells

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Back-contact solar cells are an interesting technology with advantages over traditional two-sided cells. A lack of standardized and low-cost interconnection methods inhibits their market penetration. In an attempt to overcome this obstacle, this work introduces an interconnection technology, based on a fabric of encapsulant with incorporated metal ribbons. The encapsulant is tailored for this application by adding glass fibres to a thermoplastic polyolefin. For this tailored encapsulant, characterization experiments were conducted and results on viscosity and coefficient of thermal expansion are shown. Initial reliability testing on sample-size modules with high-efficiency IBC cells shows promising results, passing up to four times the IEC 61215 standard for thermal cycling.

keywords: PV module, back-contact interconnection, advanced encapsulation materials

1 | BACKGROUND ON BACK-CONTACT INTERCONNECTION

In the field of silicon solar cell and module technology, the research focus is shifting from the conventional tabbing and stringing of two-side contacted cells to a diverse range of innovative interconnection methods. Back-contact cell interconnection is one of these. Different cell concepts such as metallization wrap-through (MWT), emitter wrap-through (EWT) and interdigitated back-contact (IBC) bring both positive and negative electrical polarities to the rear side of the cell [1]. This results in all interconnection structures being located behind the cells, which brings two main advantages. Firstly, there is no frontside shading of the cell by the interconnection ribbons, thus eliminating the need for trading off series resistance losses for shading losses when using larger interconnection ribbons. Secondly, a more homogeneous looking frontside of the solar module enhances the aesthetics. This combined increased power

yield and improved aesthetics make back-contact modules particularly suited for special applications such as vehicle and building integration. Although the benefits of back-contact cells resulted in record cell efficiencies in the past, modules using these cells still occupy only a limited global market share. To compete with ever-decreasing module prices of standard solar modules, which reached as low as 0.25 euro/Wp, a standardized and low-cost interconnection technology is required. Different parties are conducting research and multiple concepts are in different stages of their development. The following paragraphs give a brief overview of these technologies. The technologies can be classified into three main groups, depending on the methods and materials they use.

A first group includes an edge stringing [2] and a busbar stringing [3] approach and exploit methods similar to conventional tabbing and stringing of two-side contacted cells. In the edge stringing approach, the cell's metallization carries the generated electrical current towards the edge of the cell. Metal strips or tabs are soldered on edge busbars to interconnect neighbouring cells. When using standard cell sizes, high resistance losses in the cell metallization should be avoided by using a larger finger cross-sectional area. This causes thermal-induced stresses due to the mismatch in coefficients of thermal expansion (CTE) and adds to the cell material costs due to high metal consumption. In the busbar stringing approach, the metallization design of the cell contains multiple parallel printed busbars distributed over the cell metallization, allowing shorter finger length, and ribbon on busbar soldering. This reduces the resistance losses in the metallization compared to the edge stringing approach but still causes thermal-induced stresses due to CTE mismatch and the asymmetrical nature of the back-contact cells.

The second group of interconnection methods is comprised of the point-soldering [4] and solder-through stringing approach [5, 6]. In an attempt to reduce thermal-induced stresses, these approaches use back-contact cells with point solder contacts and a multi-level interconnection structure. To guarantee insulation between different electrical polarities, either insulation print (for the point-soldering) or a woven glass fibre sheet (for the solder-through stringing) is utilized. The additional insulation materials and handling steps increase the cost of the module, making it difficult to compete in the present PV module market.

The approaches from the first group start by interconnecting a set of cells - usually 10 - to form a cell string, followed by a second step to interconnect the cell strings to form a module by using tabbing ribbons. These tabbing ribbons inherently cause series resistance and active area losses. Especially this latter aspect is gaining importance, when module concepts such as shingling are competing with back-contact interconnection, partly due to their larger active area [7, 8]. The second group of approaches try to overcome this, by including advanced foils to connect all cells simultaneously. The conductive back-sheet technology [9] is under development at ECN, where a patterned conductive copper foil and insulation sheet acts as a flexible PCB-like structure. Fabricating modules using this technology requires multiple handling and alignment steps. First, conductive adhesive or solder paste is dispensed on certain locations on the conductive foil, after which a punched EVA foil is aligned so the dispensed adhesive or paste volumes are protruding through the holes of the EVA foil. The stack is further established by laying the cells on the EVA and connecting them to the conductive sheet via the dispensed adhesive or paste. A front encapsulant and glass sheet finalizes the stack, which then undergoes a laminating step during which both the EVA and the conductive adhesive cure. Initially, this technology seemed too expensive due to the relatively expensive conductive integrated back-sheet, the insulation layer, patterning and many alignment steps. Researchers now successfully lowered the cost of the conductive back-sheet by replacing part of the copper of the conductive sheet with aluminium [10], making this technology a viable competitor. The downside of the conductive back-sheet is its inability to transmit radiation. An important factor, since the International Technology Roadmap for Photovoltaics predicts a simultaneous increase in world market share for bifacial cell production and back-contact cell technologies [11]. Imec's woven interconnection attempts to overcome this, by using an interconnection foil of copper wires held in place by interwoven, continuous glass fibres [12]. This brings the advantage of reduced silver consumption and an increased power yield from the

multi-wire interconnection technologies for two-side contacted cells [13]. Cell to wire interconnection is provided by dispensed solder paste, while short-circuiting between different wires is prevented by using the glass fibres as spacers. The glass fibres are interwoven with the copper wires using a Leno-style weave. As a next innovation, we propose the 3-dimensional (3D) multi-ribbon interconnection, which carries some advantages from the latter technology such as CTE compensation by single point connections and decreased material consumption due to a tapered design, whilst potentially lowering the production costs by simplifying the design and module fabrication process. We described in more detail how the tapered design can optimize the Cu consumption in a previous publication [12]. The open character of the weave allows to interconnect bifacially active, back-contact cells. The next section will cover a detailed description of the interconnection concept. A more in-depth analysis in the progress and knowledge of the back-contact interconnection technology is beyond the scope of this paper but can be found in previous publications [12, 13].

2 | INTRODUCTION TO THE MULTI-RIBBON INTERCONNECTION

The 3D multi-ribbon interconnection method was briefly introduced at the 9th international conference on Crystalline Photovoltaics in 2019, with results on initial testing of the concept with dummy cell structures and low-performance MWT cells [14]. The concept is based on a 3D fabric of encapsulant with incorporated, solder-coated metal ribbons of which the design is shown in figure 1. The red and blue colours indicate the positive and negative polarity. The horizontal and vertical metal ribbons will be referred to as *busbar ribbons* and *cell-to-cell ribbons* respectively, named after their functionality. These two layers of metal ribbons are separated by the encapsulant to provide electrical insulation between the different electrical phases. On certain locations in the fabric, the busbar ribbons are stitched through the encapsulant, overlapping with the cell-to-cell interconnection ribbons. This overlap creates a floating connection point. The busbar ribbons are collecting generated current from different fingers and are transferring it from the cell's metallization to the cell-to-cell ribbon. The cell-to-cell ribbons do what its name suggests: transporting current from one cell to another, providing electrical connection of neighbouring cells. The cell-to-cell ribbon has just one connection point with a busbar ribbon of each neighbouring cell. Having this single connection point for each cell reduces thermal-induced stresses and potentially increases the module's reliability. By interrupting the cell-to-cell ribbons on specific locations, the fabric gets a tapered design and one ribbon can be used for two opposite polarities, which can save on the copper consumption [12].

One of the challenges of the technology is fabricating the interconnection foil in an industry-relevant way. Initial experiments did show promising results by weaving encapsulant ribbons and metal ribbons to create the fabric as described above [14]. Handling and alignment were some of the pitfalls due to the weave being too loose. Prelaminating the fabric before the module layup was initially used to solve this. Preliminary experiments now suggest that using a so-called *hybrid stitch-weaving* method to fabricate the foil enhances the fixation of the ribbons, resulting in an improved foil durability and simplified handling and alignment process. This hybrid stitch-weave method was first developed for imec's combined multi-wire interconnection for bifacial solar cells [15]. Stitch-weaving involves making two parallel cuts on certain locations in the foil after which a wire or ribbon is passed through both cuts, resulting in an inherent fixation of the ribbon to the foil. Figure 2 shows a picture of metal ribbons, hybrid stitch-woven through an encapsulant foil. For the multi-wire technology, efforts resulted in an improved foil fabrication method from manual stitch-weaving by hand to the use of a semi-automated tool. This increases the relevance of the stitch-weave method for industrial purposes. For now, the semi-automated tool can only handle wires, hence for ribbon stitch-weaving, manual fabrication is still needed. One of the benefits of the technology is the flexibility of the

FIGURE 1 A schematic overview of the design of the interconnection fabric. It consists of an encapsulant foil, separating two layers of incorporated metal ribbons: the cell-to-cell ribbons and the busbar ribbons. At certain locations both ribbons are on the same side of the foil, forming a floating connection point.

connection foil design, making it possible to be tailored for various metallization designs and cell sizes. Depending on cell performance, a trade-off between material costs and series resistance losses determines the number and size of the cell-to-cell ribbons.

FIGURE 2 A picture of metal ribbons incorporated in an encapsulant foil using the hybrid stitch-weave method.

Fabricating modules with this interconnection fabric consists of two main steps: a lay-up step and a lamination step. During the lay-up step, a stack is realized, which starts with the front glass sheet, followed by the front encapsulant foil on which the cells are placed. The fabric provides both the solder-coated interconnection ribbons and the encapsulant material for the rear side of the cells. In one alignment step, this foil is laid over the cells in such a way that each busbar ribbon is located over fingers or busbars with the same electrical polarity. With a tailored metallization design, the busbar ribbons can be soldered directly onto the fingers, omitting the need for busbar printing on the cell. This potentially cuts both processing steps and material consumption during cell manufacturing, further reducing the cost of the module. Figure 3 shows a schematic example of a possible lay-up phase, where the cell metallization consists solely of fingers.

(a)

(b)

FIGURE 3 (a) Picture of a cell on a glass and front encapsulant sheet. The cell's metallization consists solely of fingers with alternating positive and negative electrical polarity. (b) An illustration of the layup phase, where the interconnection fabric is aligned with the cell's metallization hence the positive and negative busbar ribbons are connected to the positive and negative fingers respectively.

During a vacuum lamination step, the stack is heated under pressure enabling simultaneous encapsulation of the cell and soldering of the ribbons. The solder coating of the metal ribbons starts to reflow, resulting in soldered joints both on the floating connection points between two contacting metal ribbons and on the connection between the busbar ribbons and the cell metallization. A low-melting point solder is used, which matches the temperature process window of the encapsulant. This inherently makes a more homogeneous and lower-stress solder process possible. No interconnection is created on places where the encapsulant separates two crossing ribbons. Figure 4 shows an illustration of a cross-sectional view of the module after lamination, where the floating connection points and cell to ribbon connections are visualized. One important aspect of this concept is the use of the encapsulant as an insulator, which requires a tailored encapsulant material. This will be further discussed in section 3.

FIGURE 4 A drawing of a cross-sectional view of a module with the 3D multi-ribbon interconnection, where cell-to-cell ribbons, busbar ribbons and the floating connection points are indicated.

The combined soldering and lamination reduces the number of processing steps and reduces the thermal stress due to a more homogeneous heating of the module. The concept already proved its potential for imec's combined multi-wire technology for bifacial solar cells [15], but poses challenges for the solder alloy and encapsulant material selection. Since lamination temperatures are relatively low, a low melting temperature solder is required. For PV, SnPb solder is still the most popular alloy for module interconnection due to its superior physical properties [11]. Although SnPb is still allowed for PV application, research into alternatives is growing since the Restriction of Hazardous Substances directive of the European Union banned the usage of Pb for other electronic devices in 2006. Many alloys are considered, one group being the (near) eutectic SnBi-based solder alloys, a low melting temperature type of alloy at moderate costs while being environmentally friendly [16, 17]. A melting temperature ranging from 136 °C to 139 °C at (near) eutectic compositions makes this a viable choice for the 3D multi-ribbon interconnection. Alternatively, a SnBi-based alloy with added Ag can be considered, to improve the ductility of the solder [18]. An encapsulant material compatible with this solder alloy will be implemented and is discussed in the following section.

3 | ENCAPSULANT MATERIAL SELECTION

As described earlier, combining the soldering and the encapsulation of the module manufacturing in one lamination step potentially saves costs, but also requires an in-depth understanding and controlling of the flow behaviour of both the encapsulant and the solder alloy. Plenty of experimental work related to this combined soldering and lamination is done at imec, mainly to develop imec's combined multi-wire interconnection technology [19]. Results suggest that a proper lamination temperature and associated encapsulant rheology are vital to ensure a reliable solder joint and void-free module [20]. Here, an interesting trade-off arises. On the one hand, to create a fully impregnated structure, the polymer viscosity during lamination needs to be sufficiently low. This can be achieved by using a low-viscosity polymer, a high lamination temperature or a combination of both. On the other hand, a too low viscosity leads to an excessive flow of the encapsulant, causing ribbon shifting and allowing the encapsulant to flow underneath the ribbons where it pushes away the molten solder. This hampers the formation of proper solder joints. Lowering the temperature could be a solution, were it not for the fact that the melting temperature of the solder is a limiting factor here. Previous experiments on a combined solder and encapsulation process with SnBiAg-solder show that the preferred temperature is around 165 °C [20]. To meet the minimum viscosity requirement, it was opted to use a thermoplastic polymer over the traditionally used thermosetting ethylene-vinyl acetate (EVA). The polymer used for this application is a thermoplastic polyolefin (TPO), more specifically a block copolymer consisting of different types of thermoplastic polymers and a rubber elastomer, which results in alternating soft and rigid segments [21]. Apart from its slightly higher cost, TPOs have shown to be a more suitable material compared to EVA for this application. Firstly, a TPO does not react during the lamination, hence controlling the process is easier. This also means that no byproducts are formed during lamination, which could lead to corrosion of the cell metallization and solder joints. Secondly, different authors reported a decrease in mechanical performance loss and discolouration as a result of photo-degradation compared to EVA [22–27]. TPOs are more transparent to ultraviolet (UV) light, making UV-blockers unnecessary and making them more stable for solar applications. Lastly, TPOs have shown to be more resistant to potential induced degradation compared to EVA as a result of their better insulating properties [28].

To overcome the earlier described viscosity-temperature trade-off, the authors propose an adaptation of the encapsulant polymer by adding short glass fibres, making it a composite. Due to their transparency, glass fibres could also be implemented when bifacial cells are used. Investigating the use of other fibres is beyond the scope of this work, but could be implemented for monofacial cells. The glass fibres and the polymer remain two separate, but well-mixed

phases during the whole lamination cycle. Nevertheless, many physical properties of the composite differ from the pure polymer encapsulant, especially its viscosity [29]. Using a rheometer, an oscillating frequency sweep experiment was performed to analyse the viscosity change of the composite compared to the TPO polymer. The diameter of the glass fibres ranges from 10 to 12 μm , hence using a cone and plate geometry would result in errors due to the fibres touching the cone and plate. To overcome this, a plate-plate geometry - commonly chosen for suspensions - was utilized. Circular samples with a diameter and thickness of 30 mm and 0.5 mm respectively were cut from an encapsulant foil of TPO, and TPO reinforced with 10% glass fibres. The samples were placed between the two plates of the rheometer and were kept at a constant temperature of 165 °C. Then, an angular frequency sweep from 0.628 rad/s to 62.8 rad/s was applied at a constant temperature of 165 °C. The complex viscosity was calculated from the measured loss and storage modulus. Figure 5 shows a graph of the complex viscosity as a function of the frequency of the applied oscillation. During the lamination process, the preferred shear movement of the encapsulant is limited to prevent ribbon shifting, but larger than zero to enable impregnation of all cavities. For this reason, the viscosity of interest is that at low shear rates. As expected, the viscosity of the composite is higher than its polymer matrix at all shear rates. For the composite, no clear deviation from the linear log-log relationship, which is typical for polymers, was observed. These results show that the use of glass fibres can be beneficial to the combined soldering and lamination by increasing its complex viscosity at relevant shear rates. While the composite's viscosity increased, the viscosity of the polymer phase is still equal to that of the pure polymer. As such it can flow as easily to fill small voids within the module, while the total composite is sturdy and prevents ribbon shifting and solder flow out.

FIGURE 5 The complex viscosity of a TPO and a 10% glass fibre reinforced TPO as a function of the angular frequency of the applied oscillation during an oscillating frequency sweep experiment. At all frequencies, the polymer has a lower complex viscosity than the composite encapsulant.

Adding glass fibres to the encapsulant polymer has additional benefits. Firstly, the material costs are lower, since the cost of the glass fibres is lower than that of the TPO [30]. Secondly, the added glass fibres lower the CTE of the encapsulant. As can be seen in table 1, the CTE of the other materials present in the module is lower than that of the TPO, hence lowering its CTE effectively lowers thermal-mechanical stress induced during heating and cooling of the module, potentially improving the reliability of the module.

TABLE 1 Coefficients of thermal expansion for the different materials in a solar module, where the encapsulant polymer differs from the other materials. This CTE mismatch provokes thermally induced stresses on the solder joint.

Materials	CTE ($\mu m/m^{\circ}C$)
Low Iron Glass	8.6-9.3
Silicon	2.5-3.7
Copper	16-16.7
Thermoplastic Polyolefin	100-250

To determine the impact of the added glass fibres on the CTE, both the expansion of TPO and TPO with 10% of glass fibres were measured from $-30^{\circ}C$ to $+20^{\circ}C$ using a Q400 thermo-mechanical analyser by TA instruments. The dimensional change compared to $0^{\circ}C$ for the polymer and the composite is shown on the graph in figure 6a. The CTE can be deducted as the derivative and is shown in the graph of figure 6b. For the measured temperature range, the CTE of the polymer is lowered due to the glass fibre reinforcement. Where the CTE of the polymer ranges from $125\text{--}245\text{ }\mu m/m^{\circ}C$, the composite's measured CTE is $25\text{--}45\text{ }\mu m/m^{\circ}C$, much closer to the CTE of the other materials in the module.

So far, the composite encapsulant has only been applied at the backside of the cell, but could also be implemented at the frontside for bifacial interconnection. It is expected that this has minimal effect on the transmission of light since the refractive index of glass and the TPO are closely matching. To investigate the effect on the optical performance, 1-cell laminates with 2-side contacted cells have been prepared. Only minimal differences between the composite and polymer encapsulant were observed in external quantum efficiency (EQE) and reflectance (R) measurements.

FIGURE 6 (a) The dimensional change and (b) Coefficient of Thermal Expansion (CTE) for a TPO and a 10% glass fibre reinforced TPO as a function of the temperature. The glass fibre reinforcement effectively limits the expansion and contraction of the polymer, reducing the CTE values at all measured temperatures compared to the pure polymer.

4 | RELIABILITY EXPERIMENTS

To investigate the feasibility of the concept, performance and reliability tests are carried out using 1- and 4-cell modules. This section discusses the sample preparation and the results of these experiments. At the time of the experiments, only a small batch of interdigitated back-contact (IBC) cells was available, of which the backside is shown in figure 7a. The metallization consists of horizontal fingers with alternating positive and negative polarity. Printed busbars are separated from fingers of opposite polarity by locally printed insulation pads. Tailored to this cell design, the interconnection fabrics are prepared by hand using the hybrid stitch-weave method as described in section 2. The fabric consists of a 20 cm x 20 cm TPO foil with a thickness of 0.450 mm containing 10% of short glass fibres with a diameter of 10 to 12 μm . The fabrics contain 4 pairs of busbar ribbons and 16 cell-to-cell ribbons, each with a width and thickness of 0.8 mm and 0.07 mm respectively. These copper ribbons are coated with a 5 μm to 25 μm thick layer of a SnBiAg solder. To create a tapered interconnection scheme as discussed above, the ribbons are interrupted. Figure 7b shows an image of the used fabric. Next, a stack was created of which an exploded view is shown in figure 7c. On a frontside glass sheet, a frontside encapsulant sheet and a cell (with the sunny side facing the front encapsulant sheet) are stacked. In a next step, the interconnection foil is aligned on the cell metallization. Finally, a backside glass sheet was placed on the stack. The front- and backside glass sheets each had a thickness of 3 mm. To finalize the module, the stack was then laminated at a temperature of 165 $^{\circ}\text{C}$ for 20 minutes. During the vacuum lamination, a membrane applies a constant pressure of 700 mbar. Two 1-cell modules and two 4-cell modules were prepared using the described method. A picture of the front- and backside of a 4-cell module is shown in figure 8.

FIGURE 7 (a) A picture of the backside of the IBC cell, where the metallization consists of fingers and 4 pairs of busbars. (b) The interconnection fabric tailored for this metallization design. (c) An exploded view of the stack before the lamination phase.

Current-voltage (IV) measurements were performed to characterize the initial electrical performance of the modules. Then the modules were subjected to heating and cooling cycles according to the IEC 61215 standard for thermal cycling reliability experiments. Intermediate IV characterization measurements were performed on the modules and figure 9a shows the results for the two 1-cell modules. For both samples, there is no clear sign of degradation with the fill factor dropping from 75.8% and 77.2% to 75.3% and 77.1% after 200 cycles. After 800 cycles, the fill factors dropped to 73.6% and 76.6% - a relative decrease of 2.9% and 0.8%. For the two 4-cell modules, the same procedure was repeated. The degradation in fill factor is shown on the graph in figure 9b. One of the 4-cell laminates had a lower initial fill factor caused by a failure of the insulation print on cell level. Both samples passed three times the IEC61215 standard test, with the total power output at the maximum power point changing from 19.45 W and 20.18 W to

FIGURE 8 (a) Front- and (b) backside of a 4-cell module with the multi-ribbon interconnection.

18.98 W and 19.89 W respectively. The fill factor remained relatively stable, reducing from 71.3% and 74.9% to 70.3% and 74.5% after 600 cycles respectively. These results demonstrate the module reliability in thermal cycling and prove the feasibility of the concept. They also prove that the encapsulant can act as a stable insulator between ribbons and cell metallization of opposite polarity.

FIGURE 9 Results of the reliability experiments for (a) two 1-cell and (b) two 4-cell modules. For all samples, very limited to no decrease in fill factor was observed.

5 | CONCLUSIONS

This work introduced a novel interconnection technology, based on a hybrid stitch-woven fabric of encapsulant and incorporated metal ribbons. The metal ribbons form a 3D structure where the encapsulant provides electrical insulation between ribbons of opposite polarity. The technology attempts to increase reliability by using single connection points and a tailored composite encapsulant while being cost-effective due to its optimized material consumption and

reduced processing steps. The glass fibre reinforced polymer encapsulant was characterized using thermomechanical analysis and dynamical mechanical analysis to prove its potential for solar module fabrication. Its lowered CTE could be beneficial to decrease CTE mismatch, while an increased viscosity can enable a combined soldering and encapsulation, reducing the total number of processing steps. Reliability experiments using thermal cycling and electrical characterization were used to show the potential of the interconnection technology. Two sample-sized 1-cell modules with IBC cells show very limited degradation after 800 thermal cycles, and two sample-sized 4-cell modules show no degradation for at least 600 cycles.

data availability statement

The data that support the findings of this study are available from the corresponding author upon request.

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