Advances in module interconnection technologies for crystalline silicon solar cells

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Abstract

In the evolution towards higher cell efficiencies, new cell concepts (two-sided and back contacted) have been introduced and for each of these concepts, new module materials and interconnection technologies have to be developed to fulfil all the demands of a good end product in terms of lowest costs, highest yield and power and above all superior quality (reliability and durability). There is no single module concept that fits all cell concepts or module application type so existing module concepts need to be adapted or innovative module technologies are required to fit the aforementioned requirements. This paper provides an overview summarizing the recent developments of integrated cell to module manufacturing approaches such as multi-busbar, multi-wire, half-cell and shingling technologies for two-side contacted cells and advanced soldering, woven fabric and foil based module technologies for back contacted cells aiming for the highest power outputs, lowest costs and longest lifetimes.

Introduction

The current market is dominated (>95%) by crystalline-Si (x-Si) technology; and predominantly by the traditional Al-BSF p-type cell technology that has already been the standard technology for several decades. The cell efficiencies range from 18% for multi- to >20% for the best performing mono-variants.

In the race towards the highest efficiencies for single junction x-Si cells, the trend is from multi to mono, from p- to n-type wafers and from two-side-contacted towards back-contacted cell concepts. At the same time an increasing number of cells will become light sensitive on both sides, so-called bifacial cells. The anticipated evolution, according to the insights of the PV community, of the average stabilized cell efficiency in mass production for all cell concepts on different wafer materials is reflected in the annual recurring ITRPV roadmap predictions [1]. Figure 1 shows the expected trend as published in the most recent edition of 2018.

The present insights confirm that the market will be dominated by the two-side-contacted cell types with an increasing share of PERC/PERT/PERL concepts to become mainstream after 2020. Despite the fact that heterojunction (HJT) and back-contact (MWT, IBC) cell concepts have proven a very high efficiency potential by module producers such as Panasonic, SunPower and Kaneka, their market share is expected to grow slower with expected shares of 15 and 10% in 2028 respectively.

As the solar cells are the basic units of the final PV system and not the final product, these individual cells are integrated into a module where cells are connected in series to add up voltage and generate the power characteristics that are useful for a practical application. The basic design of solar modules has not changed for many decades and most improvements have mainly relied on innovations at the cell level. However, the introduction of advanced and high-efficiency cell concepts revealed the limits of standard module technology and therefore highlighted the need for novel approaches towards module integration. Each cell concept has to be individually evaluated for the optimal module interconnection in terms of:

- Cell-to-module (CtM) power ratio
- Optimized production costs reflected by high yields and low investment costs
- Optimized bill of materials (BoM) at the lowest costs
- Best energy yield reflected by temperature, low light and incident angle behaviour
- Application fit: monofacial versus bifacial
- Reliability and durability guaranteeing more than 30 years' product lifetime under various climate conditions
- Sustainability and recycling potential as an emerging metric

This combination of requirements in terms of maximum module power optimization, long-term reliability and low-cost pressure has resulted in growing research efforts from R&D institutes and module manufacturers to improve PV panel output power independent of the cell efficiency developments [2]. The research progress translates into an increased CtM power ratio which is an acceptable metric to assess developments at the module level. Two complementary approaches that are followed to influence CtM power ratio can be summarized as:

1. Applying light management strategies using innovative module materials e.g. anti-reflection coatings, reflective busbars and backsheets
2. Reducing the resistive losses by increasing ribbon cross section, number of busbars, multi-wires, downsized cells, and conductive backsheets

Combining Figure 1 with the predicted increase of the CtM power ratio leads to Figure 2 and shows the trend curve as depicted by ITRPV for a typical 60 module with 156 x 156 mm^2 cells [1].

In this paper, we provide an overview of the current research and development trends in module interconnection technologies for (p- and n-type) two-side-contacted and back-contacted x-Si cell concepts that could be retrieved via the public channels. We are fully aware that this overview is not exhaustive as there are certainly module technologies under investigation by companies that have not disclosed their approaches in the public domain.

Standard interconnection of two-side-contacted cells into modules

Today, the most common PV module fabrication technology involves stringing of two-side-contacted photovoltaic cells. The generated electrical current is collected through distributed metal fingers across the cell into typically two or more busbars. By soldering of tinned copper ribbons to these busbars, cells are electrically connected in series to form cell strings, as illustrated in Figure 3. The size of these ribbons is a compromise between shadowing on the illuminated surface of the cells and resistive losses. The individual cell strings are connected with string connection ribbons and laminated into a module.

Evolving into more and more distributed stringing interconnection…

For both improving electrical performance and reducing optical losses, a trend towards an increasing amount of busbars is materializing [1]. Indeed, for the same amount of material, a lower resistive loss can be obtained by decreasing the finger losses or alternatively for the same loss, less material is needed. In terms of optics, more narrow ribbons will result in a reduced reflection out of the module and thus enhance light recycling, yielding a higher current. Culminating this trend are multi-wire interconnection technologies, with the additional advantage that busbars are no longer needed on the cells and the conductivity of the fingers can be strongly reduced, decreasing the cost of the silver metallization on cell level. This is illustrated in Figure 4.

- Increasing the amount of busbars (2-5-15) reduces the resistive losses in the fingers: the current is collected closer to where it has been generated in the cell, resulting in lower finger currents and thus lower resistive losses
- Switching from rectangular ribbons to round wires (while keeping the same total cross-section) yields reduces optical (reflection) losses due to the enhanced light trapping within the module [3]
- Using thicker wires, the total cross-section is increased and the resistive losses in the ribbons are reduced, though the thicker wires induce an additional optical (reflective) loss

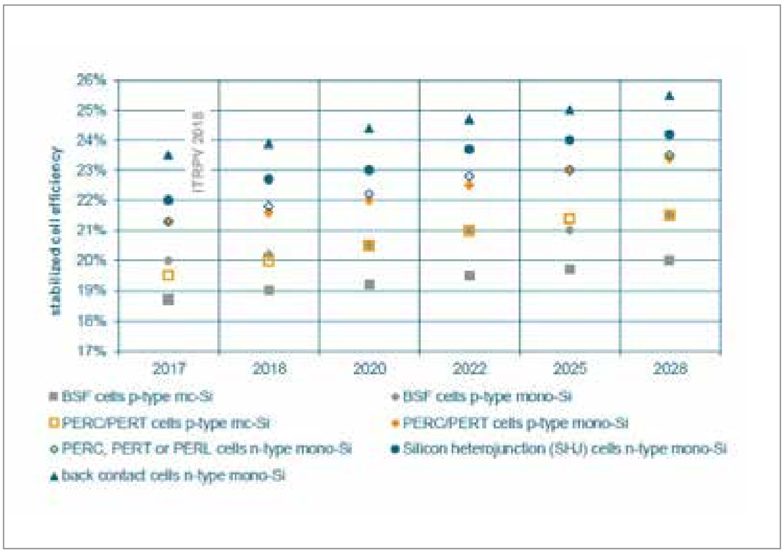


Figure 1. The projected development of average stabilized efficiency values for various x-Si cell types from the ITRPV roadmap 2018 edition [1].

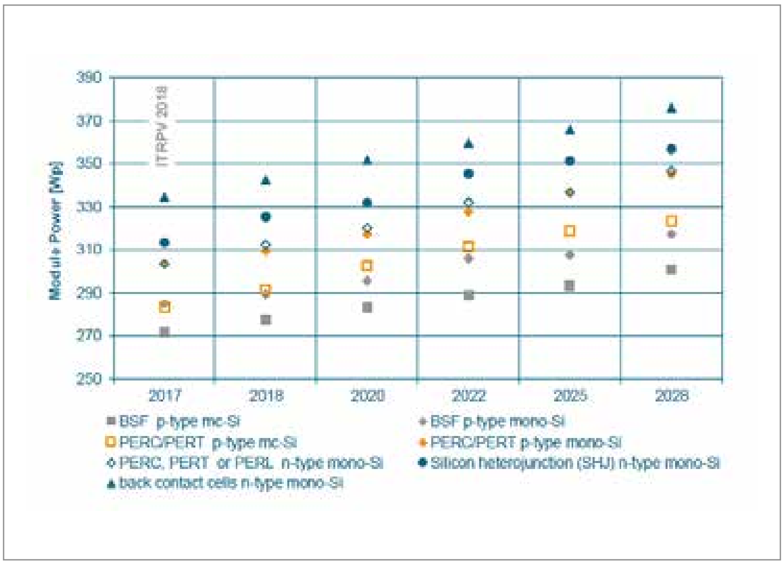


Figure 2. The projected development of module power values of 60-cell modules for different x-Si cell types in the ITRPV roadmap 2018 edition [1].

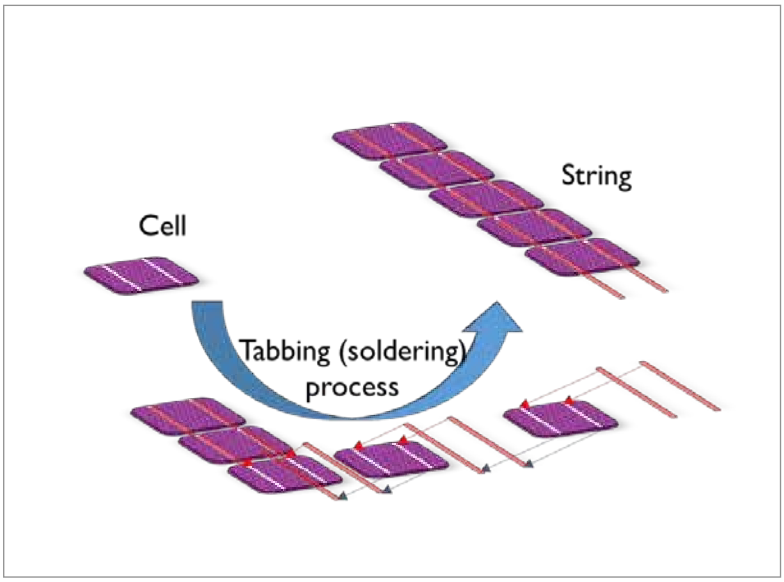
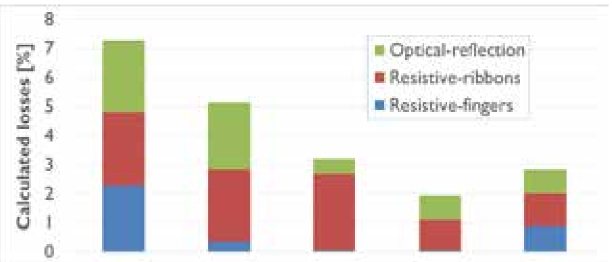


Figure 3. Standard interconnection of two-side-contacted cells into strings is achieved through alternatingly laying down and soldering of cells and ribbons in the so-called tabbing process.



# busbars	2	5	15	15	15
Ribbon/wire section	2x0.3 mm²	0.8x0.3 mm²	0.16 mmØ	0.25 mmØ	0.25 mmØ
Finger section [mm²]	0.1x0.02	0.1x0.02	0.1x0.02	0.1x0.02	0.02x0.005

Figure 4. The relative impact of amount and cross-section of ribbons/wires, and cross-section of fingers in (calculated) resistive and optical losses due to interconnection (illustrative numbers, assuming fixed amount of fingers and finger and ribbon conductivity).

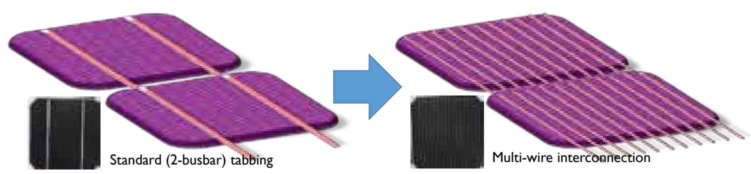


Figure 5. Illustrating the evolution in appearance (small insets) and interconnection scheme from standard (two-busbar) tabbing (left) to multi-wire interconnection (right).

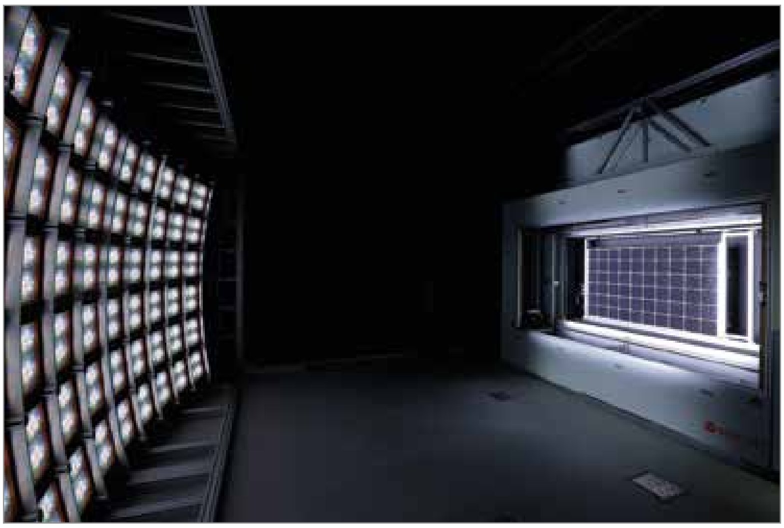


Figure 6. A commercial multi-wire soldered Neon module from LG acting as a reference module during flashing.

- Making the trade-off with cost, the finger metallization could be reduced, though at the expense of additional resistive losses

Apart from the electrical and optical benefits, also the aesthetics are improved, yielding a darker (cf. reduced optical losses) and more uniform module surface, as indicated in Figure 5.

Two such multi-wire interconnection technologies are in a very advanced stage of development. One approach effectively mimics the standard technology by soldering on finger solder pads, replacing the busbar [4]. As in standard production, this step is then followed by a separate encapsulation process through vacuum lamination. Such an approach requires controlling wire expansion during the soldering process and alignment of the wires to the finger pads. High performance and reliability has been demonstrated with this approach, and is already in volume production by LG [5], reaching 340Wp and 20% module efficiency.

… and merging with module-level encapsulation

A second approach applies a contact foil directly onto the metallized cell followed by a lamination process; this is the so-called Smart Wire Connection Technology (SWCT) [6]. The contact foil integrates low-temperature-solder-coated copper wires on an optically transparent supporting film with an adhesive layer. During the lamination the wires of the contact foil are soldered directly to the metal fingers of the cell. The use of low-temperature solder reduces stress between the wire-to-finger contact points on the cell. The contact foil is produced with the wires alternating on opposite sides of the supporting film, to allow the wires to contact neighbouring two-side-contacted cells to realize a series interconnection. Similarly as for the first approach, stress considerations may require some attention for compensating differences in thermal expansion between the cells and the wires, and an additional layer of encapsulant material is used for the subsequent module lamination step.

In its latest version, Meyer Burger has demonstrated 60-cell modules with heterojunction (HJ) cells reaching 335Wp, based on In-free soldering and UV-transparent encapsulation (white tiger foils) [7]. It also publishes good reliability results up to 2-3 times IEC testing for damp heat and thermal cycling, for both glass-glass and glass-backsheet modules. Commercialization of this HJ cell and module technology is gradually starting up.

Building further on these evolutions, and bringing in weaving knowhow, imec is looking into the replacement of the contact foil with a woven interconnection sheet allowing to similarly combine interconnection and encapsulation in the lamination step, though without introducing additional materials. Such a woven sheet can be manufactured by weaving metal wires perpendicularly into encapsulant ribbons. The weaving process immediately allows the metal wires to protrude on both sides of the fabric and thus can be also contacted electrically on either side.

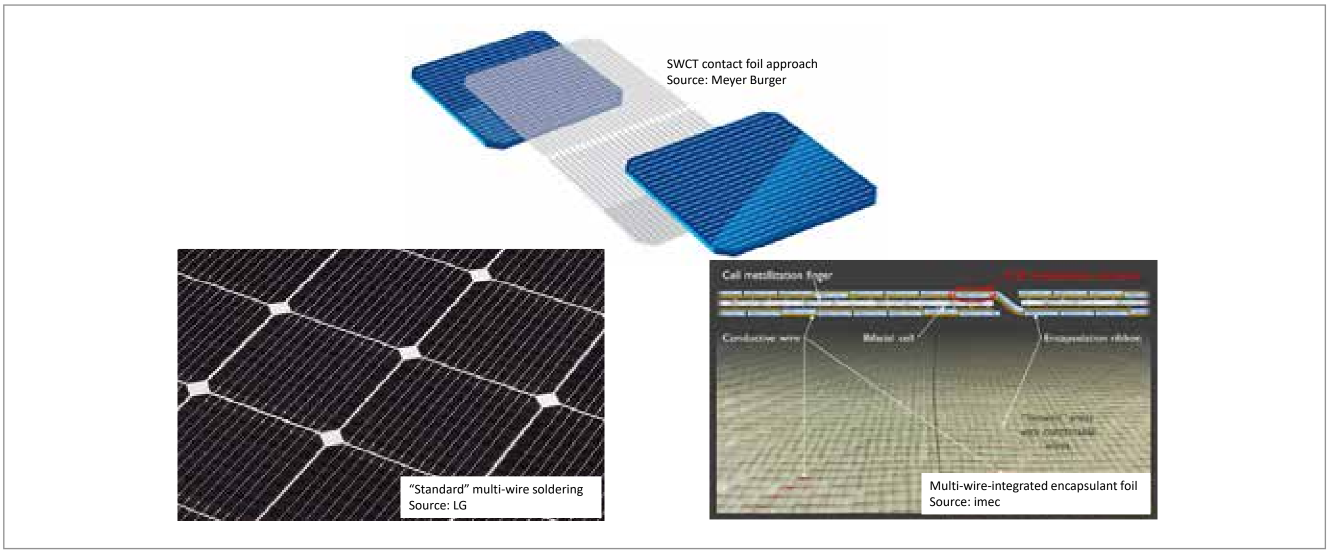


Figure 7. Illustration of the discussed multi-wire interconnection approaches.

If the cell metallization is designed with diagonal fingers on the backside, also the large ribbons to interconnect the strings can be left out. Layup of cells and interconnection fabrics can then be done immediately on the module glass, ready for feeding into a standard laminator where soldering and encapsulation is simultaneously achieved. Promising proof-of-concepts have been reported [8].

Soldering revisited

For these last evolutions, where the soldering process takes place during lamination, the standard solder materials, typically SnPbAg alloys, can no longer be used due to their melting temperatures in the range of 180°C, which is too high for most laminators. To reduce the melting temperatures, SnIn- and SnBi-based alloys are being investigated intensively [9], with a clear preference for Bi, considering the significantly higher cost of In. As a side note, also the transition to Pb-free soldering has sparked some development effort in solder materials by e.g. Alpha providing a leadfree drop-in replacement based on a SnBi-alloy [10]. First adopter of the low temperature solder alloy is the HJ cell technology, which also cannot withstand the above 200°C solder temperatures required by SnPbAg alloy. A recent review in this journal details further the technical challenges of the metallization and interconnection of this cell type [11]. The trends towards Pb-free solder might be limited now although the rising ecological concerns and novel legislations might force a rapid adaptation of these materials beyond HJ cells.

Reducing the interconnection current to reduce resistive losses: cutting cells

One rather simple solution to improve the module power and reducing the CtM losses without changing the standard interconnection technology is by using half cut cells, and this has a significant impact on the performance of PV modules. The power increase is mainly due to the reduction of resistive losses, which is achieved by halving the cell current and thereby increasing the fill factor (FF). This is simply because the electrical losses are proportional to the sum of the products of the resistances with the square of the flowing currents via the relation:

$$P_{loss} = \sum R \times I^2$$

The power loss is reduced by a factor of four when current is divided by two. In addition the extra spaces between the cells can be used to enhance reflections within the laminate, for instance by using white encapsulant layers (EVA, Polyolefins) on the rear of the cells and the backsheet resulting in short circuit gains. Both effects overcompensate the connectivity losses to a large extent, resulting in power boosts of up to 3-4% relative compared to standard technology. Additionally, junction boxes with bypass diodes can be attached in the middle of the strings, making the modules more tolerant to operation in conditions with partial shading [12], although on the other hand this involves the application of split junction boxes in the middle of the module, complicating standard manufacturing technology and bifacial considerations.

Moreover, an additional step is needed to slice the full size cells into half pieces and this needs to be done with a maximum yield and minimization of the efficiency losses caused by imperfections at the cut edge and an overall higher edge-to-area ratio. Significant improvements have been made in the development of thermal laser separation and mechanical breakage techniques [13,14] to overcome this limitation, further supported by advanced modelling approaches [15]. Additionally, modification of the stringer equipment in the module manufacturing line is required when moving to half cells to maintain the same throughputs. This has not precluded the big Tier 1 module manufacturers like REC, Jinko, Trina, Canadian and JA Solar to increase their production capacity of half-cell modules by further fine tuning their fully automated processes, representing a smooth evolution of their existing production lines [2]. Nearly any cell technology can be used to make half cells and it is very likely that the market share of half-cell technology will significantly increase in the coming decade up to 40 % in 2028 as predicted by ITRPV [1] especially in market segments where aesthetics plays a less prominent role.

Getting rid of the wiring material: shingling

Another interesting module concept that is based on the interconnection of sliced cells is the so called shingling or tile based interconnection technology [2]. The whole concept is by no means new and dates back to 1956 as was extensively described in a recent review on singulated-cell and module architectures by Wöhrle et al [16]. The approach towards shingling was at that time largely motivated by particular design requirements and the need for high power densities on smaller available areas like car roofs. With the steady growth of the PV sector and the wish to diversify and differentiate, the potential of shingling technology has been rediscovered by a few large module manufacturers like SunPower that acquired shingle pioneer Cogenra in the recent past and commercializes the technology under its brand name P-series [17].

The beauty of this technology is that it eliminates the presence of ribbons, which clearly improves the aesthetics of the panel. A wafer sized cell is sliced into 5-6 rectangular stripe cells which are connected from the leading edge of the front cells to the opposite edge of the rear cell similar to the way roof tiles are constructed. The availability of flexible electrically conductive adhesives (ECA) as a low stress interconnecting material as well as suitable processing equipment strongly promoted the renewed interest of this technology. A schematic layout of the interconnection of shingle cells is shown in Figure 8.

The technology offers several advantages, including [18]:

- Low electrical losses due to the lower currents of the smaller shingle cells
- Improved area utilizations because of the denser packing of cells
- Processing at lower temperatures since ECA's are cured at lower temperatures than traditional tab soldering
- Smaller currents could lead to lower operating temperatures thereby improving energy yield and durability
- Application to any cell type (except back-contact) and the potential to make it bifacial
- Aesthetical appeal improves considerably because of the absence of busbars and ribbons

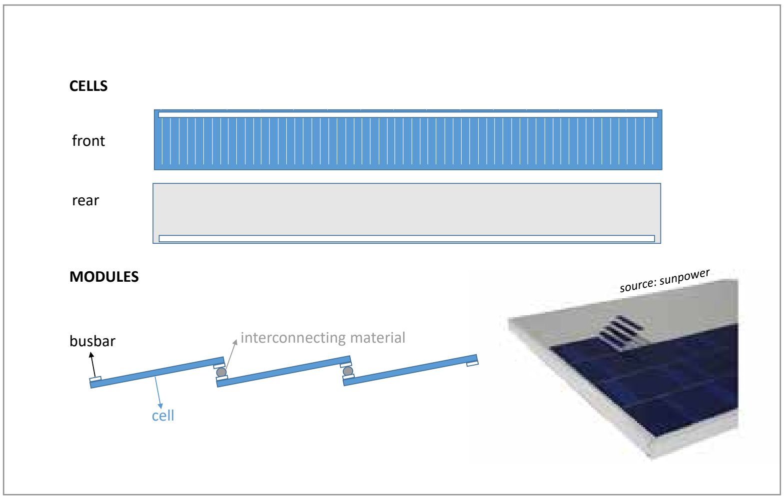


Figure 8. Schematic layout showing the principle of shingling module technology: above a top view of a monofacial sliced cell with busbars at the leading edges of front and rear cells; lower left a cross section of the interconnection of the sliced cells via an interconnecting material and lower right how cells are integrated in a full size module. Source: SunPower.

Singulation

As with half cut cells, the separation process step to cut down the full cell into stripe cells is done with laser-assisted cutting and subsequent mechanical cleavage. Specific attention should be paid to edge passivation to minimize recombination losses because of the higher edge-to-area ratio. To identify the optimum cell design with respect to cell width and corresponding front metallization finger grid design, simulations on the power output for cell stripes are carried out for standard Al-BSF cells [19] and for the so-called 'shingled passivated edge, rear emitter and rear' (SPEER) bifacial concept invented by Fraunhofer ISE [20]. This type of simulation can be applied for any future high-efficiency shingle-based cell concept based on passivated contacts leading to even higher module powers.

Interconnection

A very important requirement in a successful integration of shingled cells into modules is to create a reliable electrical interconnection between the cells that withstands the thermomechanical stresses that the module will undergo during testing and real-life operation. The interconnecting material should be flexible enough to avoid early failures due to the mismatch of thermal expansion coefficients and ECAs appear to be the most suitable class of materials that match the requirements [18]. These materials can be delivered as pastes and consist of a mixture of Ag particles within a matrix that is either based on silicones or organics. The ECAs are typically cured at temperatures between 150 and 180°C, after which the Ag particles form a percolative network and become highly conductive. The ECAs can be applied by either screen/stencil printing or dispensing/jetting. The choice of ECA as well as an optimized curing profile is required to get optimal

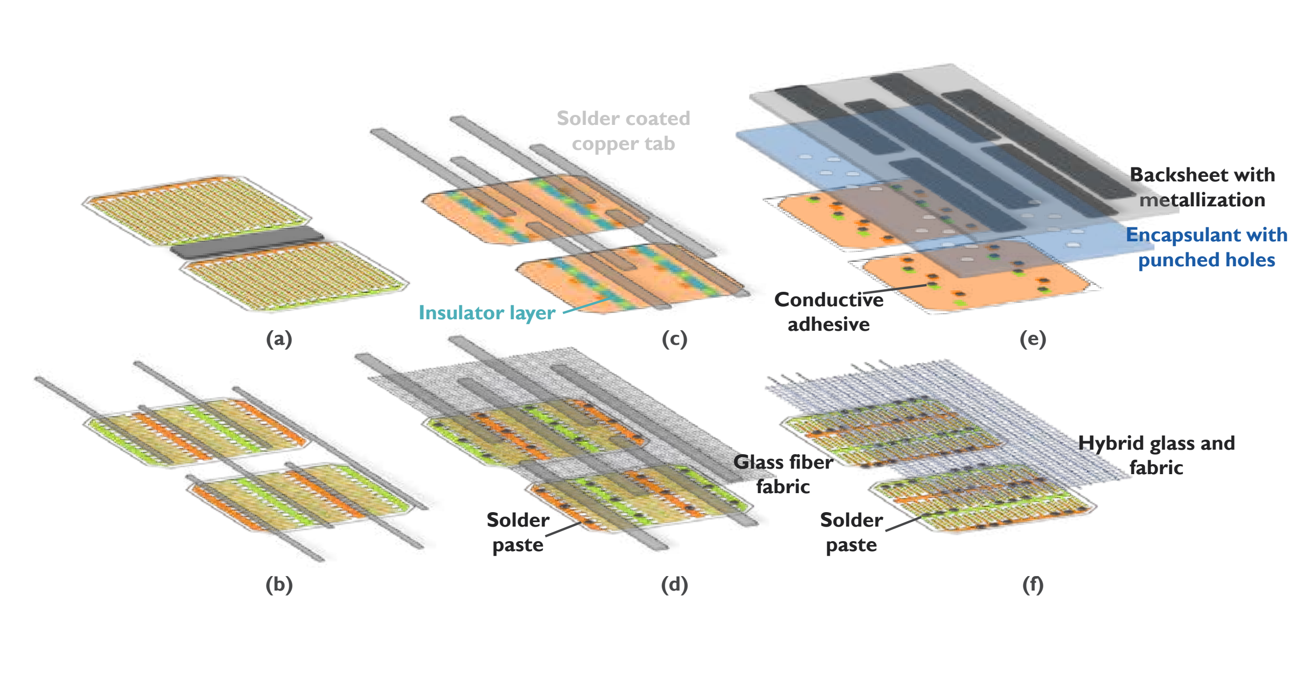


Figure 9. Schematics of various interconnection approaches for back-contact cells: (a) edge stringing, (b) busbar soldering (c) point soldering, (d) solder-through stringing, (e) foil-based interconnection and (f) woven multi-wire interconnection fabric (figure reproduced from [25] with permission).

adhesion and to pass all the critical failure tests. Some of these material challenges were addressed in a paper by Beaucarne et al. [21] where a simple analytical model was described to determine the conditions needed to avoid interconnection joint failure. It was found that interconnection materials with a low ratio of shear modulus G over shear strength is preferred for a good and robust interconnection joint. This clearly showed that ECAs with low $G/\tau_{shear\ stress}$ stress are superior over stiff solder joints to achieve sufficient string robustness and long term reliability.

An accurate CtM analysis done by ISE [22] revealed a clear improvement of the CtM ratio in terms of efficiency and power up to 10 % relative compared to conventional modules with ribbon or wire cell interconnection. This was further confirmed by experimental studies [22].

Concerning the long-term reliability of shingling module technology there is not a long history of test and field data so a thorough assessment cannot be made at this stage despite encouraging temperature cycling data showing <3 % power loss after 800 TC cycles [18]. SunPower further claims that its Performance Series panels are very robust since they were named as a top performer in five critical reliability tests: thermal cycling, damp heat, humidity-freeze, dynamic mechanical load and potential induced degradation as was reported in the DNV GL PV module reliability score card 2017 [17, 23].

All in all, the regained attractiveness of shingle technology has triggered the interest of more manufacturers (Seraphim, Solaria, GCL, TZS) than frontrunner SunPower, which could lead to an increased and significant market share in the coming decade.

Interconnecting back-contacted cells into modules

Despite the fact that the PV market is dominated by cell concepts which have the contacts on both sides of the cell, the world record efficiency of 26.6 % is obtained with a back-contacted cell where the current collection and contacts are all at the rear of the cell [24]. The p-n junction and metallization grid are made up of alternating parallel lines making an interdigitated pattern which gives the cell its name: interdigitated back-contact (IBC). As there is no metallization on the front of the cell, a higher current can be reached than for the two-side-contacted cells.

Another type of back-contacted cell is the metal-wrap -through cell, shortened to MWT. Here current is collected at the front and rear of the cell, but the current on the front is transported through holes or vias in the cell which are filled with a silver metallization paste to contacts at the rear of the cell. The front side contacts are isolated from the rear of the cell to prevent a short circuit. The advantages of this type of cell are the reduced metallization coverage on the front of the cell due to the absence of busbars allowing a higher current to be generated than with a standard two-side-contacted cell. Current collection is spread over the whole cell making it more efficient with lower resistance losses.

For both IBC and MWT cells, different module technologies are required to interconnect the cells due to the back-contact design. Below, we will review a number of module technologies that are currently applied in industry and various research institutes as are shown in Figure 9, largely based on and updating a previously published overview [25].

Edge stringing (Figure 9a)

SunPower is the best known manufacturer of IBC cells and produces high power PV panels for quite some years now for the high end market with module efficiencies over 22 % [26]. The cells are made of high grade n-type silicon. The metallization on the rear is completely different from conventional cells. Electroplated interdigitated copper fingers coated with tin adhere very well to the silicon and form a highly conductive pathway to busbars that are positioned at the edges of the cell. These busbars are connected using a smart tab which is designed to minimize the thermal stress on the cell during operation. The tab provides the electrical interconnection between neighbouring cells and sufficient strain relief if cells expand and shrink during temperature cycles (see Figure 10).

The edge stringing approach in fact decouples the cell interconnect from the cell contact metallization. While an elegant approach in this respect, it also implies that the cell metallization has to carry the current of the full cell. This leads to a trade-off in terms of cell metallization thickness: a low resistance requires a high thickness, however mechanical stress, as well as cost considerations ask for a thin metallization. Indeed warping due to a mismatch in coefficient of thermal expansion (CTE) between the silicon and the metallization can result in mechanical stress or cracking, which reduces the yield both in cell fabrication and module assembly. As the effect scales with size, SunPower balances this trade-off in metallization thickness by implementing this approach while keeping a limited cell size.

SunPower claims that because of this fundamentally different module design and BoM a superior reliability in real world conditions can be achieved. This was confirmed by continuous extensive qualification test programmes well beyond industry standards, supported by additional characterization and modelling, finally resulting in degradation rates <0.2 % for the optimized module designs [26,27].

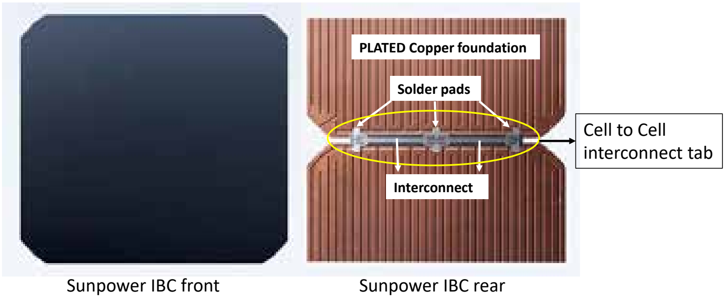


Figure 10. Layout of the edge stringing approach of IBC cells as applied by SunPower. Source: SunPower, https://us.SunPower.com

Busbar stringing and point soldering (Figure 9b and 9c)

An alternative approach to overcome this trade-off is the busbar stringing approach, where the interconnect metallization on top of additional busbars within the cell area can reduce the need for a thick cell metallization [28]. In this approach, however, some electrical performance is lost as some active area is sacrificed for the busbars, causing electrical shading, unless the busbars are implemented in a second metallization level (floating busbars) [29,30,31].

To reduce electrical shading by the cell metallization, while maintaining reduced resistive losses at module level, multi-level interconnection technologies are developed. These approaches require a more closely linked cell and module metallization design. Among them the point contact approach [32] is an interesting solution as the classical tabbing, where the conductive tab is directly placed over the cell, is compromised in back-contact cells due to shunts between different polarity fingers. To avoid this shunting an isolator is needed after cell fabrication (whereas in the floating busbar approach this isolator is deposited as part of the cell process). In some approaches this isolation function is also performed by the encapsulant [32]. More similar to printed circuit board assembly technology, this function could be realised by a solder mask. Another approach inspired by microelectronic circuits uses an adapter [33]. Lately, work has also been ongoing to integrate a multi-wire approach in such an isolator-based scheme [34].

Solder-through stringing (Figure 9d)

An innovative way of significantly reducing the cost is put forward by the solder-through stringing approach, where the insulation is guaranteed by a porous insulator, e.g. a woven glass fibre sheet through which a solder paste reflows and provides contact between cell contact and ribbon [35]. This approach is being commercialized by Soltech [36].

All of the above approaches use similar (solder) materials and tabbing-stringing technologies as developed for two-side contacted cells. After stringing, where cells are interconnected, these strings are traditionally then interconnected at the edge of the modules by metal (bussing) ribbons in the so-called bussing step. This implies additional resistive and area losses in the module [37, 38]. To overcome these losses module-level interconnection technologies are of interest and therefore under development. Additionally, they also enable multi-level metallization, hence reducing the thickness requirements for the cell metallization, and the elimination of a separate cell soldering step and string handling opens the door for thinner cells.

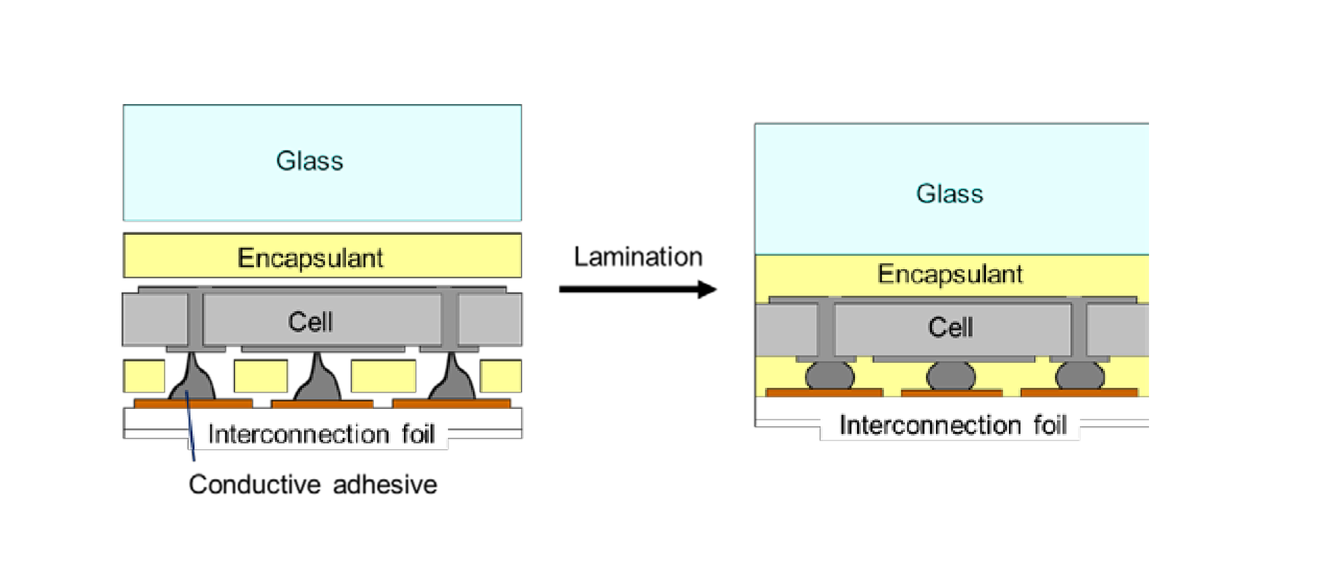


Figure 11. Schematic layout of the foil-based back contact module layer stack before and after the lamination process.

Foil-based back contact (FBC) interconnection technology (Figure 9e)

At ECN an integrated module technology for back-contact cells was developed using a back-sheet foil with an additional conductive metallic layer, usually copper or aluminium [39,40]. The conductive layer is patterned by milling, etching or other techniques to match the contact pattern on the rear of the cell so as to form a series interconnection between neighbouring cells. Contact between the cells and the copper layer is made using an interconnection paste, usually an ECA or low-temperature solder, which is applied onto the foil or the cell by stencil printing or dispensing/jetting. The cells are isolated from the foil via a layer of encapsulant with holes at the position of the conductive material. The thickness of this encapsulant layer dictates the amount of conductive material needed. The cells are then placed on top of the encapsulant and adhesive and the stack is finished with a second layer of encapsulant and a glass sheet (see Figure 11).

FBC modules have been shown to reduce cell-to-module losses when compared to other mature module technologies (soldering/tabbing and multiwire) since the total conductor cross section in FBC modules is significantly higher than for the other interconnection types [41], thereby reducing the resistive losses. FBC modules mainly based on MWT cells have proven to be reliable in selected climate chamber testing (damp heat and temperature cycling) and long-term outdoor testing, and IEC certification for MWT modules with well selected BoM has been achieved by ECN and partners [42, 43].

Dedicated industrial manufacturing equipment is available for the module manufacturing and has a very high level of automation like for instance demonstrated by equipment manufacturers as Eurotron, FormulaE and Valoe [44]. The first industrial production towards the gigawatt scale has recently started in China at Sunport Power [45], while production activities in Netherlands at a smaller scale have been started or announced [46].

In order to reach a competitive cost structure compared to the current mainstream, a large-scale industrial implementation of FBC module technology requires development of the complete value chain and availability of the materials in large volumes at low cost, in particular the conductive back-sheet and the ECA. The cost of the back-sheet is partially related to the processing used to pattern the foil and partly to the cost of the metallic conductor. The cost of the ECA is dominated by the silver content.

Recently, a number of strategies have been reported by ECN [47] to further reduce the costs of FBC technology and are summarized below:

1: Replace copper by aluminium

Originally, the patterned metal used in the conductive back sheet is a thin layer of ~35 micron copper (Cu) foil that is glued to a polymeric PV backsheet. Replacing the Cu layer in the conductive back-sheet with aluminium (Al) has the potential to reduce the overall cost of the module by more than 2% since Al is inherently cheaper than Cu. However, Al forms a native oxide on its surface which should result in an unacceptably high contact resistance to the ECA. One solution to overcome this has been explored and commercialized by the company Hanita who developed a low-cost alternative to copper foil by coating the aluminium layer with an ultrathin copper skin by Physical Vapour Deposition methods [48].

Alternatively, ECN has demonstrated the use of a cold-spray technique [40,49,50] by which Cu particles are deposited via lanes onto the Al surface at very high speeds, breaking through the oxide and making contact to the bulk Al (see Figure 12). The back contacted cells are contacted via the rear to

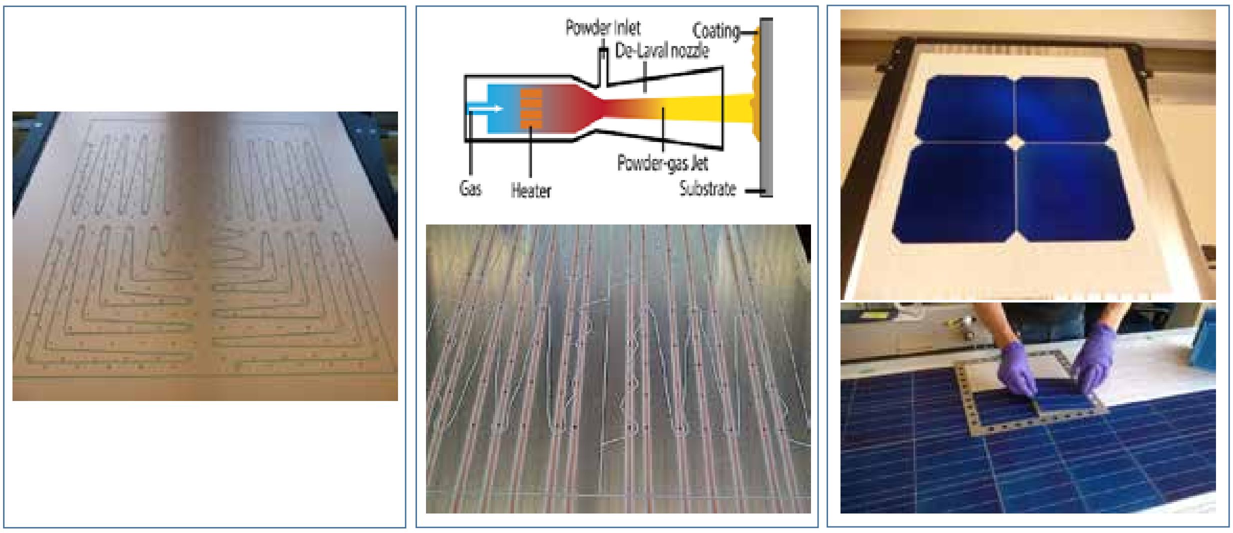


Figure 12. From left to right: a patterned copper conductive backsheet (left), a schematic representation of the spray gun used for the cold spray process and an aluminium foil with sprayed copper lines corresponding with the position of positive and negative contacts (middle); an IBC 2x2 cells mini module and the manufacturing of a MWT full size module based on copper sprayed aluminium conductive back sheets.

the Al foil via the Cu particles through an ECA with contact resistances down to 0.2 mΩ. guaranteeing a negligible CtM fill factor loss due to the interconnection. Large series of 2x2 MWT and IBC cells mini-modules have been manufactured in the ECN pilot line using this approach and are subjected to selected standard IEC reliability tests for damp heat and thermal cycling. The ageing tests clearly reveal the technical potential of the cold spray method by demonstrating >95 % power retention after three times IEC and are in line with the best test results of modules built with Cu conductive back contact foil. A prototype full size MWT module was recently manufactured at ECN with a CtM FF loss of less than 1.5 % [47].

2: Optical enhancements

FBC is also well suited for carrying the larger currents produced by larger cells, IBC, or modules with enhanced optical elements with lower resistive losses. This is because the foil makes contact at multiple points distributed across the entire cell area creating a parallel path for current conduction. Therefore, optical enhancements, such as placing a reflective material between cells (intra-module foil, IMF) can be optimized for overall improved power output for back contact modules. A highly reflective intra-module foil (IMF) is placed in all the currently inactive areas of the module, between cells and along the edges in order to reflect light back onto the high efficiency cells as can be seen in Figure 13.

As noted above, similar materials are currently available and used in standard modules. ECN has demonstrated the IMF with back contact mini-modules with 5% CtM power gain for both IBC and MWT cells [51]. For full sized 60-cell MWT modules manufactured on an existing production line for FBC modules, a CtM of more than 4% has been demonstrated [47]. To achieve this, the space between the cells was increased to 10.5mm and 6mm in the height and width respectively resulting in a 6.3% larger module area. This is then filled with IMF material. This results in more 7% gain in module power and approximately 1.5% gain in total area module efficiency.

3: High yield with thinner wafers

Another way to reduce the cost structure of PV is to save on Si usage and use thinner wafers for cell production. Since thin cells are more fragile in handling a suitable module technology is required to maintain the same production speed and yield. FBC technology, which uses pick-and-place equipment for cell placement was used to make such thin cell modules possible as was recently reported [47,52,53,54]. A larger series of ~95 µm thin n-type IBC cells were manufactured using an industrial compatible process flow [54] starting from 120 µm thick 6 inch n-type Cz diamond wire cut wafers. A selection of 60 thin-cells (process based on homojunctions and not fully optimized) with a narrow efficiency distribution was made for integration in a full sized module based on FBC module interconnection technology using dedicated industrial equipment from Eurotron and a standard module bill of materials (BoM) including ECA's. The module was produced without any breakage of cells and a cell-to-module (CtM) power loss of less than 1% while only minor issues of micro-crack formation were observed with EL. This demonstrates the feasibility of FBC technology for handling thin cells down to 80 micron thickness.

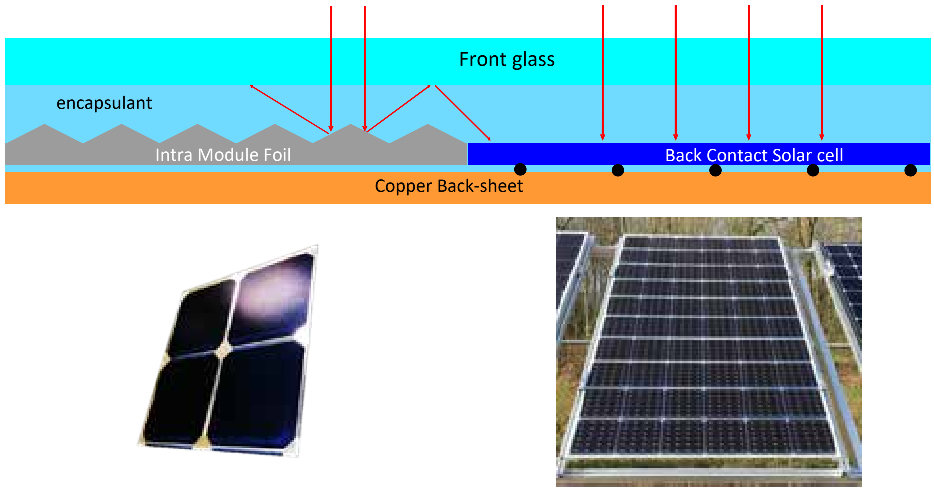


Figure 13. Upper: schematic cross-section of a Foil-based back contact module combined with reflective Intra-Module Foil (IMF). Lower left IBC mini-module with 8mm wide IMF integrated along cell edges and corners, lower right: full size 60-cell MWT module using IMF materials to increase the current by almost 6%.

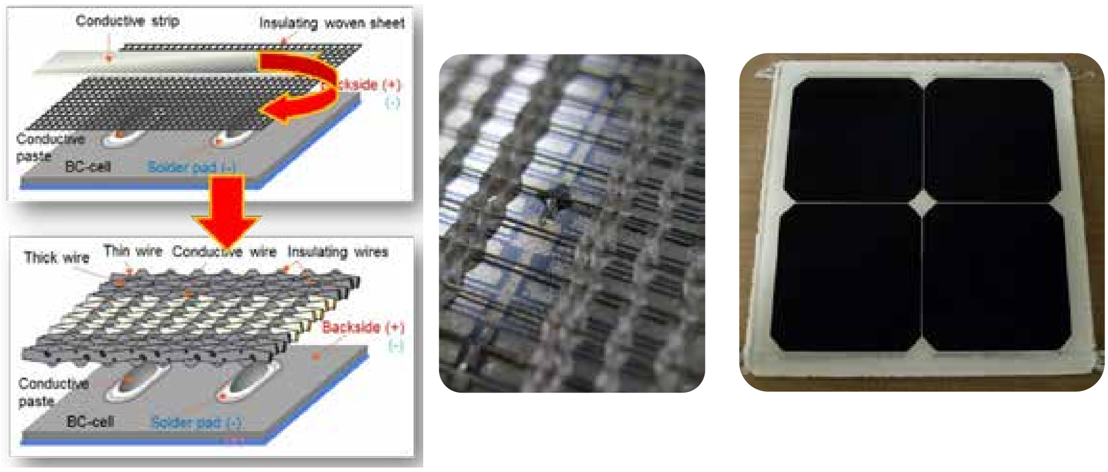


Figure 14. Schematic (left) and detail (middle) of how the interconnecting conductive ribbons in the solder-through approach can be integrated inside the woven fabric and applied in a 2x2-cell-module (right).

Woven multi-wire interconnection fabric concept (Figure 9f)

Another concept is under development at imec [35,55]. This concept is inspired by the earlier-mentioned solder-through approach and additionally brings some of the opportunities from the multi-wire interconnection technologies under development as the SWCT and MBB (multi-busbar) approach [56,57,58]. Although these are propagated mainly for two-side contacted cells currently, and not for back-contact cells, there are some features that could similarly prove beneficial here:

- Optically (not at the front obviously, but) potentially at the back for bifacial cells compared to conductive backsheets, due to the open weave structure;
- Mechanical reinforcement of the encapsulant including resilience to thermal cycling due to a reduced CTE of the glass-fibre-reinforced encapsulant;
- Reliability due to a reduced impact of cracking with the distributed wiring;
- Reduced cell metallization requirement (reduced resistance) due to the distributed contacting.

In this novel concept, insulating glass fibre and conductive wires are integrated into a hybrid woven fabric, as indicated in Figure 14. Compared to the solder-through approach, where wide metal ribbons are connecting neighbouring cells in series, the proposed novel concept uses an array of metallic wires to replace those tabbing ribbons. The metallic wires are interwoven with glass fibres to fix the metal wires' location and isolate them from the backside of the cell. Connection between the cell metallization and the metallic wires in the fabric is made through locally deposited solder paste dots. This requires an open weave pattern for solder spreading. One weave pattern that satisfies these requirements is the so-called leno weave, where pairs of fibres are twisted during the weaving process to provide an interlocked fabric. This technology can be implemented both on string and module level. The latter is achieved by integrating metallic wires at the side of the fabric in the perpendicular direction to the wires interconnecting the cells, hence enabling connection of the cell strings directly in one soldering step.

This approach of weaving together glass fibres and thin metallic wires can bring multiple improvements compared to existing interconnection technologies.

Firstly, module performance can be improved by allowing an increased metal cross-section between cells while maintaining a uniform topography of the fabric with a porous structure that can be embedded by the encapsulant. Additionally, the interconnect metallization is on a different level than the cell metallization, which allows to reduce the requirements for the cell metallization in terms of current collection (resistive losses).

Secondly, this interconnection can be designed to address strict reliability requirements through a number of features. To limit thermally-induced stresses, distributed out-of-plane stress relief in the metal wires can be easily designed and implemented into the woven fabric, e.g. by using glass fibres of different diameter within the same fabric. Though soldered contacts typically entail higher stresses than conductive adhesives [58] (but are still generally considered more reliable), multiple and distributed solder points can reduce and even eliminate the build-up of stresses across the cell. A homogenous and reduced heating over the full area during soldering creates a more homogeneous stress across the cell than local heating. With such a more evenly distributed stress, the maximum local stress may be lower, further lowering the risk of cracking compared to standard tabbing approaches. A uniform topography of the interconnecting fabric can further reduce mechanical stress on the cells and eases the lamination in glass-glass modules. Indeed, as the interconnection can be separated from the encapsulation process, the technology also allows freedom in encapsulation system, with glass-glass encapsulation eliminating humidity ingress through the backsheet which may be beneficial depending on the used encapsulation scheme and environmental conditions during operation [60]. Apart from this, realizing a more symmetrical build-up of the module is beneficial from the perspective of mechanical and thermomechanical stress on the cells inside [61]. Also, considering reliability, the used materials such as glass fibre and solder paste have already been previously validated in other PV module concepts [62] and as such lower the unknown factors that are often considered a barrier in PV module technology.

Thirdly, this selection of known materials potentially allows a low-cost technology. Weaving technology simultaneously, at limited cost in high-volume production, adapts easily to various cell metallization layouts. Avoiding the necessity of a separate stringing step and the potential of solder paste for self-alignment allows a simplified module assembly. In module assembly the ease of optical alignment due to open weave structure and relaxed alignment accuracy can also be a considerable bonus. Finally, the porous structure of the fabric allows the encapsulant to penetrate the fabric, which can thus be embedded in the encapsulant layer and potentially, depending on wire and fibre dimensions and composition, minimizes the amount and therefore cost of encapsulant material.

Concluding remarks

In the evolution towards higher cell efficiencies, new cell concepts (two-sided and back-contacted) have been introduced and for each of these concepts, new module materials and interconnection technologies have to be developed to fulfil all the demands of a good end product in terms of lowest costs, highest yield and power and above all superior quality (reliability and durability). There is no single module concept that fits all cell concepts and module application type so existing module concepts need to be adapted or innovative module technologies are required to fit the aforementioned requirements. This paper provides an overview summarizing the development of integrated cell-to-module manufacturing approaches such as multi-busbar, multi-wire, shingling module technologies for two-sided contact cells and advanced soldering, woven fabric and foil-based module technologies for back contact cells aiming for the highest power outputs, lowest costs and longest lifetimes.

With this increasing number of approaches that deviate from standardly applied technology, a versatile "toolbox" is generated to design various kind of tailored products for different applications and needs with the aim to further widen the applicability of PV. Especially by benefiting from unique features of a specific module technology or combinations thereof, specialized products can be made that are tailored for new application areas such as:

(i) BIPV (building-integrated PV), e.g. PV modules integrated in the facade of buildings, integrated in the roof of buildings, integrated in windows, …
(ii) IIPV (infrastructure-integrated PV), e.g. PV

modules for sound barriers along highways and railways, PV modules integrated in roads, in-city applications such as street lightening, sub-urban and rural applications, floating PV modules...

(iii) Transportation, e.g. PV modules for cars, trains, buses, aircrafts, ...

(iv) Climate optimized PV: PV modules which are optimized for maximum energy yield in a specific climate, such as desert climate, cold and snowy climates, climates with high humidity, continental climates with large daily and yearly temperature variations...

For these emerging application fields additional criteria like improved aesthetics, flexibility of shape and size, shadow tolerance, increased resistance towards extreme weather conditions, bifaciality, three-dimensional shaping etc. are becoming more important to specify the final product. The existence of multiple module technologies, concepts and associated bill of materials might facilitate the selection whatever suits best.

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