Bifacial solar cell interconnection technology: A bird's-eye view

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Abstract

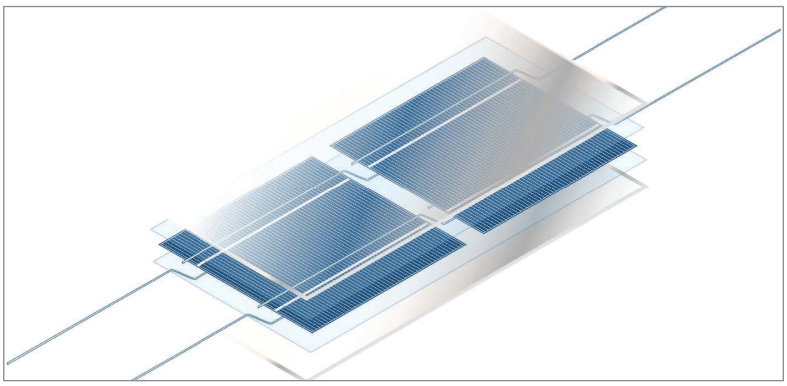
The recent trends in crystalline Si-based bifacial cell development are having a major impact on interconnection technology. This paper presents an overview of various bifacial interconnection technologies. Starting from traditional tabbing and stringing, the discussion elaborates on developments in multi-wire interconnection technology, and subsequently examines the concept of shingling bifacial cells. The overview concludes with the latest developments in bifacial back-contact cell interconnection technology.

Introduction

Although bifacial cells implement a few changes at the solar cell level compared with their monofacial counterparts, this is not necessarily the case for the method used to interconnect the cells. Indeed, the most widely adopted way of interconnecting bifacial cells and creating modules is still based on the very traditional approach involving double-sided interconnection of the cells by soldering metal ribbons between the front of one cell and the rear of the neighbouring cell, to create cell strings.

An increase in power resulting from new trends in cell development, however, reveals the limitations of this technology in terms of optical–electrical trade-off for the finger grid. In addition to this evolution, the trends towards thinner cells and heterojunction technology (HJT) severely compromise the temperature budget for the interconnection technology [1]. Addressing this issue, a lower-temperature interconnection technology reduces thermal stress caused by differences in thermal expansion of interconnection materials.

Several technologies are being developed to fulfil these requirements. Apart from drop-in replacements of the soldering compounds in the traditional approach with low-temperature versions or electrically conductive adhesives (ECAs), some very promising options are based on multi-wire interconnection technology, besides other developments in the area of shingling. A bit further afield, but no less interesting, are some interconnection technologies related to back-contact bifacial cell development.



Source: imec

Figure 1. Exploded view of a standard cell string.

Traditional tabbing and stringing of solar cells

The most traditional technology that is compatible with bifacial cells is based on tabbing and stringing of cells with solder-coated copper ribbons. The generated electrical current is collected through distributed metal fingers across the cell into typically nowadays three to five printed busbars (BBs). By soldering tinned copper ribbons to these busbars between opposite polarities of the cells, the cells are electrically connected in series to form cell strings. The size of these ribbons is a compromise between shadowing on the illuminated surface of the cells and resistive losses.

After the lay-up of the strings – and string interconnection using thick bussing ribbons – between encapsulant sheets and a front and back transparent protective layer, a vacuum lamination step is performed. This method of cell interconnection and module fabrication is very well documented and described by Wohlgemuth and Narayanan [2], among others, and is in many cases applicable to bifacial cells. Fig. 1 shows an exploded schematic view of a cell string in a glass–glass laminate stack.

Currently, 3BB cell designs are widely used, but the share of 4BB designs is on the increase, together with 5BB designs (as also predicted by the ITRPV roadmap [1]). Increasing the number of busbars will reduce the current build-up in the printed fingers of the cell metal grid, as more conductors are distributed over the cell surface crossing the fingers. This leads to lower resistive losses in the fingers, enabling smaller finger cross-sections, and better optical yields and lower metallization costs at the cell level.

High-efficiency grooved interconnection ribbons have been developed to compensate for the shading effect of the ribbons; by adding grooves in the ribbons, more light is scattered and reflected on the glass–air interface of the module, improving internal light capturing (Fig. 2).

Although PV modules are currently excluded from the restrictions imposed by WEEE and RoHS guidelines, the motivation to look at interconnections free of lead and harmful substances is becoming more and more important and is partly driven by the emerging changes in environmental

Source: Ulbrich

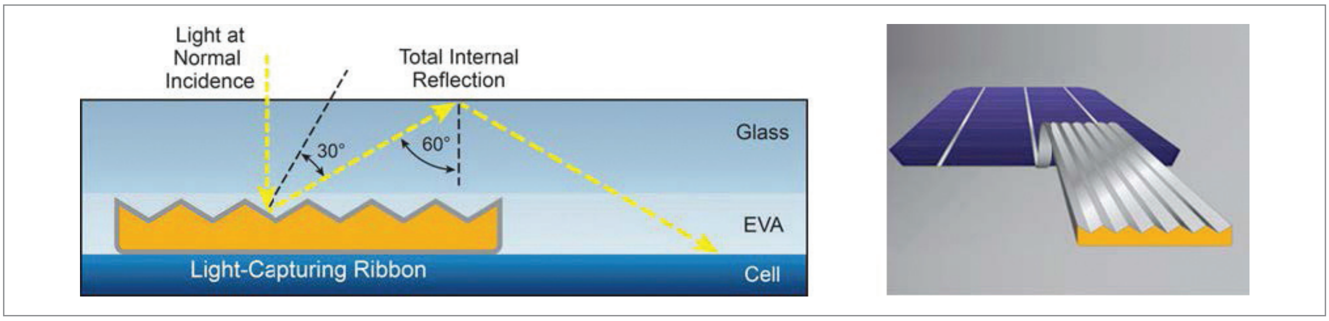


Figure 2. Ulbrich LCR-XP™ light-capturing ribbon.

Source: LG

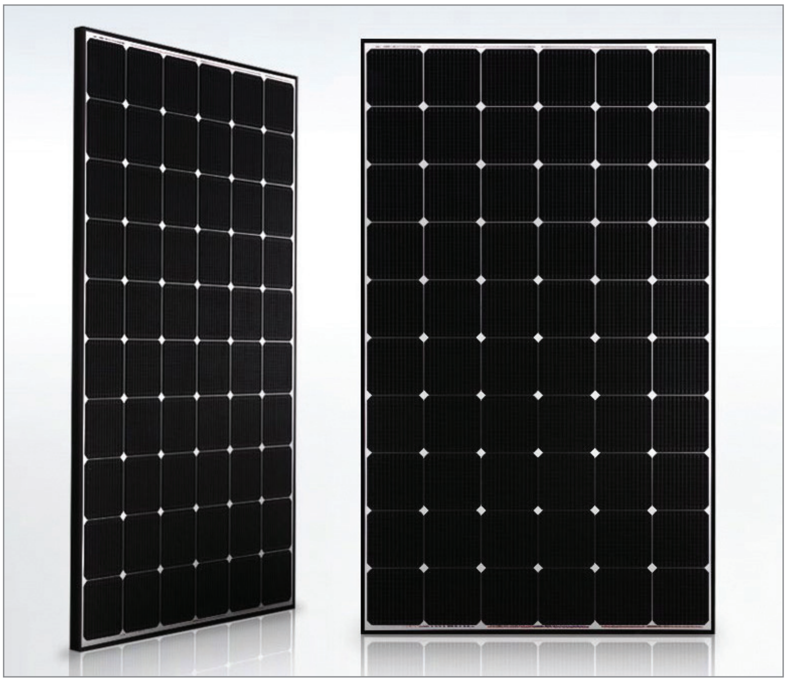


Figure 3. LG NeON module with Schmid multi-busbar (MBB) technology.

"The motivation to look at interconnections free of lead and harmful substances is becoming more and more important."

legislation that could potentially limit the use of lead; after all, in addition to regular updates on substance restrictions, the European Commission will be reviewing the RoHS Directive and is expected to prepare a new proposal by 2021 [3,4].

It is difficult to find an equivalent alternative to this widely used solder; the use of tin- and tin–copper-based solder is limited to applications that are not affected by its higher melting temperature [5]. Low-melting-point solders are often characterized by higher brittleness or poor cell contact wetting characteristics, although Bi-based alloys are also under development [6].

To achieve both objectives – low-temperature and lead-free interconnection – ECAs are also being considered, despite their higher cost. The ECA can be applied as a tape between the ribbon and the cell, or printed on the cell. This technique allows the interconnection of cells with thicknesses below 160μm as a result of better thermal stress management during the interconnection process and thermal cycling [7], and because of the lower bonding temperatures than those encountered with standard solder processes based on tin, tin–lead and tin–copper.

In addition, there have been growing efforts to reduce the lead (and silver) content in the metal paste material for the solar cell. Secondly, to meet the temperature-budget restrictions during cell production, low-temperature firing pastes have been developed. However, both these developments also have an impact on the cell interconnection technology.

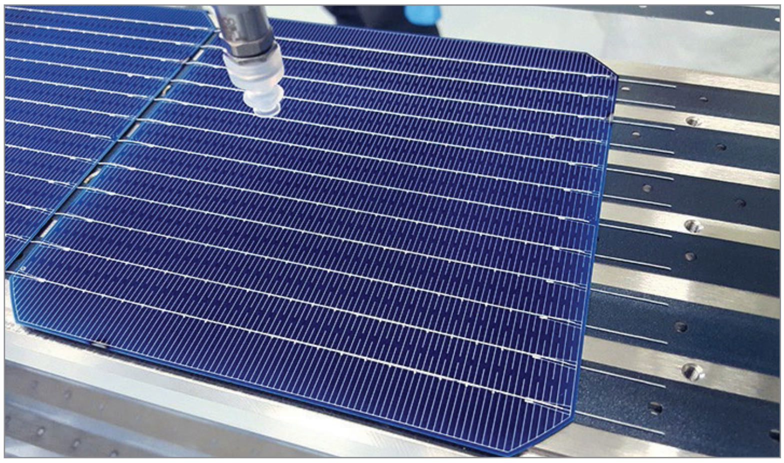
Multi-wire technology

Multi-wire based on tabbing and stringing

To reduce the resistive losses in the cell fingers, as well as the costs associated with the cell metallization grid, a further evolution of the tabbing-ribbon approach has been developed and implemented by Schmid, making use of stringing busbar-free cells with multiple round wires (Schmid multi-busbar technology; see Fig. 3). This multi-wire interconnection technology has been introduced for double-side contacted cells [8,9]. Since the peel forces achieved on soldered wires are limited for wires directly soldered onto fingers, small solder pads are predicted to increase the soldered area. Nevertheless, as no full busbars are used, a significant reduction in shadowing and/or inactive area is achieved.

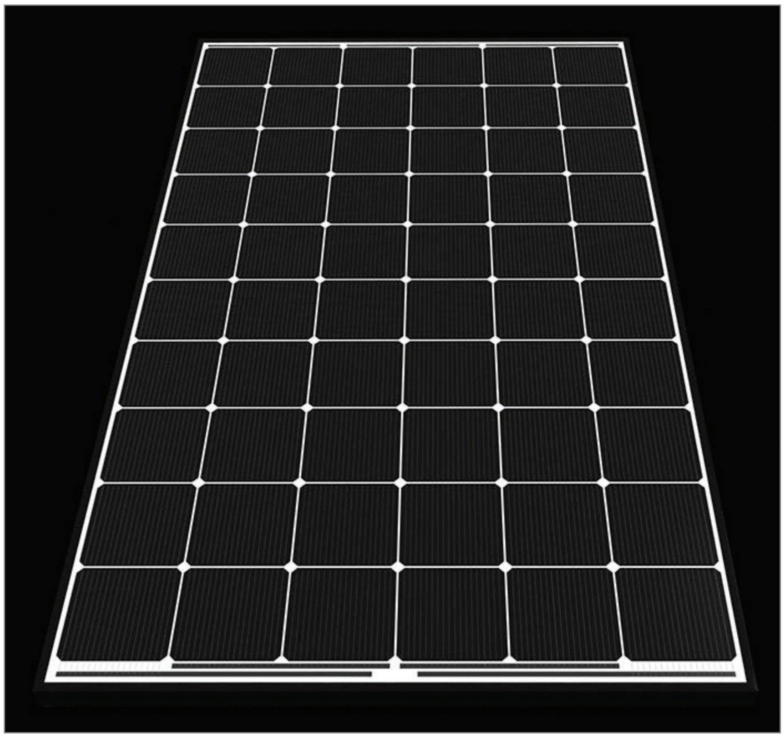
A distributed network of typically 15 round metal wires replace the three to five metal busbars. This eliminates the need for cell busbars, and finger length is drastically reduced, allowing a saving on the finger metallization without increasing ohmic losses. Resulting in reduced shading losses, the round metallic wires can attract a considerable performance advantage, as the round shape of the wires promotes internal light scattering, leading to more internal reflection and thereby improving light harvesting. A $0.33\%_{abs}$ higher performance of MBB versus the established H-pattern solar cell has been demonstrated [4].

Schmid's MBB technology for cell tabbing and stringing is similar to traditional tabbing and stringing. To assemble MBB modules, existing module lines can simply be upgraded by replacing the tabber and stringer machine by a dedicated stringer machine (Fig. 4) (provided the cell metallization grid is adjusted accordingly).



Source: Schmid

Figure 4. Schmid MBB connector machine.



Source: SolarTech

Figure 5. SolarTech Universal EPIQ module based on SWCT technology.

Multi-wire based on pre-laminated contact sheets

Not too long ago, Meyer Burger introduced its SmartWire Connection Technology (SWCT™), a technology that was first put forward by Day4Energy [10], and further industrialized by Meyer Burger. SWCT combines multiple wires with a polymer foil to create an interconnection foil; the copper wires are coated with a low-melting-point solder (Fig. 5).

The interconnection foils are pre-laminated on busbarless cells to form strings (Fig. 6). After the lay-up between outer protective glass sheets and encapsulant sheets (similarly to the two previously described methods), the stack is laminated in a vacuum laminator. During this lamination process, a low-temperature solder interconnection with the cell metallization fingers is established: the temperature of the lamination process is sufficient to melt the low-melting-point solder on the copper wires and form an intermetallic connection between the wires and the cell fingers. This temperature budget is also compatible with the process window of the encapsulant material [11].

SWCT technology also benefits from improved light recycling, resulting in better optical and electrical performance, similar to that of the Schmid approach. Additionally, even more wires can be used more easily (typically 18, but up to 24), as the specific (albeit small) contact pads used for the Schmid approach can be avoided. In consequence, more

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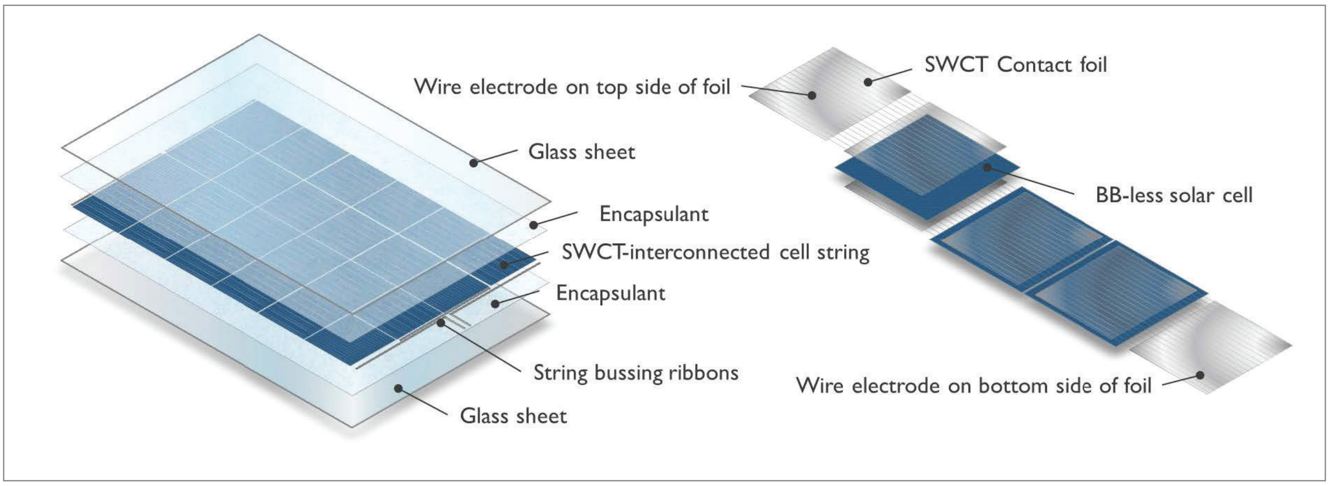


Source: imec (drawn by imec)

Figure 6. SWCT cell string build-up.

redundancy is created in case of cracks or occasional defective solder joints.

A major advantage of SWCT technology is its compatibility with applications that demand low-temperature interconnection – a particularly important factor for heterojunction solar cells.

Source: Meyer Burger

Figure 7. Meyer Burger IBEX SWCT stringer.

Source: imec

Figure 8. Example of a 4×4-cell module incorporating imec multi-wire interconnection technology.

Moreover, the technology is compatible with cell thicknesses as low as 120µm [12]. As the solder is lead-free, this technology also addresses future RoHS guidelines concerning hazardous substances.

Although Meyer Burger's SWCT deviates significantly from Schmid MBB technology, the required changes to the process flow are in principle confined to an adaptation of the cell stringing process (Fig. 7). Instead of pre-soldering wires on the cell, the stringer in this case pre-laminates the SWCT foils on the cells to create strings. The actual solder interconnection of the wires and fingers is established during the subsequent lamination step, after the lay-up of the pre-laminated strings in the module stack on a lay-up station.

Multi-wire based on encapsulant-integrated contact sheets [13,14]

Building further on the evolution towards a low-temperature interconnection technology consisting of multiple wires, imec is developing a system whereby the contact foil is replaced by a woven interconnection sheet combining interconnection wires and encapsulation material (Fig. 8). The idea behind this method is to provide enough encapsulation material in the contact sheet to allow a single lamination step for both lamination and interconnection, without introducing additional materials.

The contact sheet can be made by combining low-temperature solder-coated copper wires, interwoven perpendicularly with encapsulant ribbons (Fig. 9). The metal wires extend over both sides of the woven fabric, and can therefore also be contacted electrically on both sides. Finger contact is enhanced by means of a diagonal progression of an intertwining of the wires along the weave (twill lines).

Because of the weaving process, out-of-plane thermal-stress-relief features are integrated into the sheet, created by the undulating shape of the woven wires (alternately contacting the cell metallization and floating above the cell), which reduces thermomechanical stress generated after soldering or during thermal cycling.

An alternative method for weaving is also in development: here, the wires are directly introduced into an encapsulant sheet through locally implemented cuts according to an optimized cutting pattern for contact and stress relief (Fig. 10).

Because no prior stringing or tabbing of solar cells is required, the lay-up of the module layers can be started immediately by placing the front or back glass in the lay-up station. A contact sheet is placed on the glass, with the contact side facing up (i.e. the side where the wires mostly protrude from the weave). The first (bifacial) cell is laid on this side. A second sheet is laid on the cell, with the first contact-side half facing down. The next cell is laid on the second half of this contact sheet (i.e. the half where the contact side is facing up). This procedure is continued to create cell strings.

Any orientation of the contact sheet relative to the fingers of the cell would be possible, providing that a diagonal orientation of the finger metallization grid on (at least one side of) the cell is foreseen. Strings can therefore be connected by turning contact sheets perpendicularly to a cell string, thereby avoiding the use of end-bussing ribbons between two cell strings. This would considerably reduce the amount of Cu consumption in module manufacturing and avoid time-consuming and production-yield-restricting process steps. The lay-up is schematically illustrated in Fig. 11.

As a final step, a second protective glass sheet is positioned. Depending on the outer borders of the module, no additional encapsulation material is needed. The lay-up can be done in an automated lay-up station, as shown in Fig. 12.

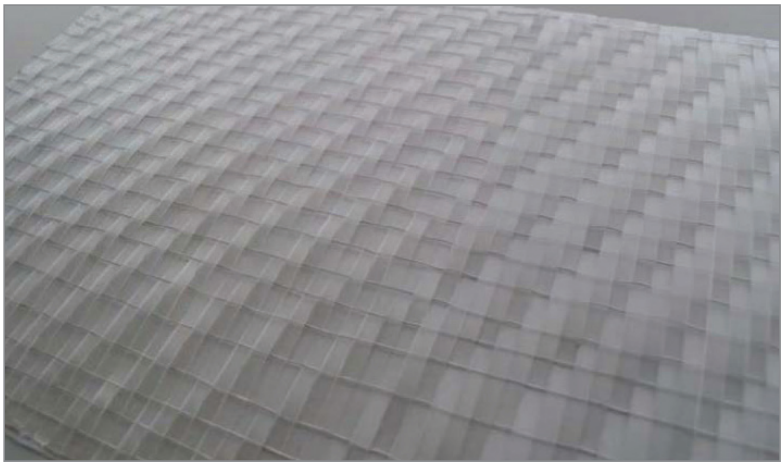
During the subsequent vacuum lamination step, the copper wires are soldered to the metal fingers of the cells. The wires are coated with a lead-free tin–bismuth-based low-melting-point solder.

Initially, the polymer material is not fully liquefied in order to avoid the penetration of encapsulant material between the cell fingers and the wires, which might lead to poor electrical solder contacts. A further increase in temperature causes the thermoplastic encapsulant ribbons to melt, transforming them into a uniform encapsulation layer (Fig. 13).

Shingling technology

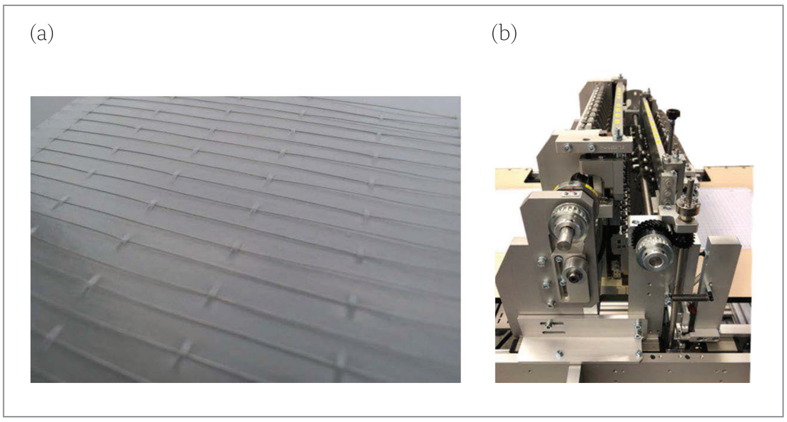
Another, very different, approach for two-side contacted cells that is gaining popularity is based on shingling (Fig. 14). Although an old concept in PV interconnection, it is now rapidly attracting interest in the industry because of some very interesting features. The significant erosion of cell prices has assisted the progress of shingling, the main drivers being an increased active area, a decrease in electrical losses, and a straightforward string assembly.

While current commercial modules typically target monofacial applications and superior aesthetics (rooftop BAPV), there is no reason why shingling could not be employed in a bifacial application with a suitable metal grid design on both sides of the bifacial cells. As cells are cut (typically into five or six strips) to reduce cell metallization grid resistive losses, the current in the cell string is reduced, leading to lower resistive losses. No additional wires or ribbons are needed, thus avoiding shading on the cells, and allowing a very straightforward assembly process. The overlapping method in the shingling approach allows an increased active area of the



Source: VdS Weaving

Figure 9. Example of a woven interconnection sheet.



Source: IPTE

Figure 10. (a) Finished sheet with locally 'stitched' wires. (b) Process unit of an IPTE proof-of-concept contact sheet processing machine.

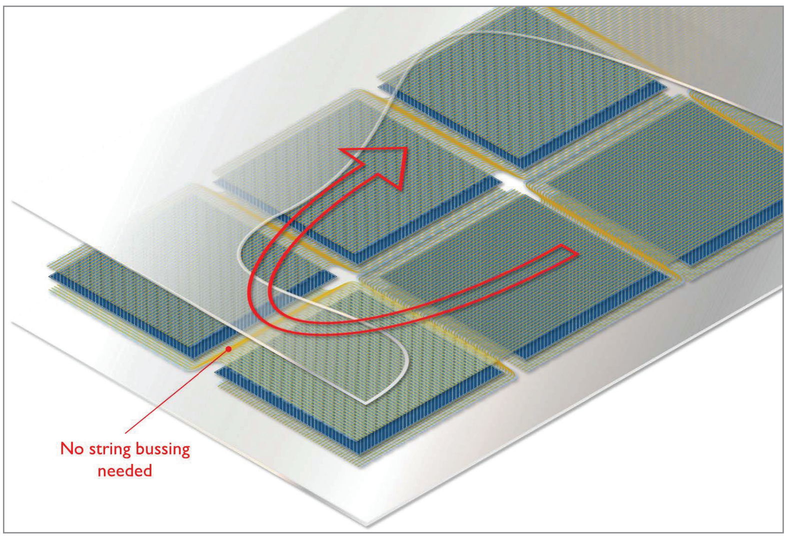


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Figure 11. Exploded view of multi-wire technology module lay-up, based on encapsulant-integrated contact sheets.

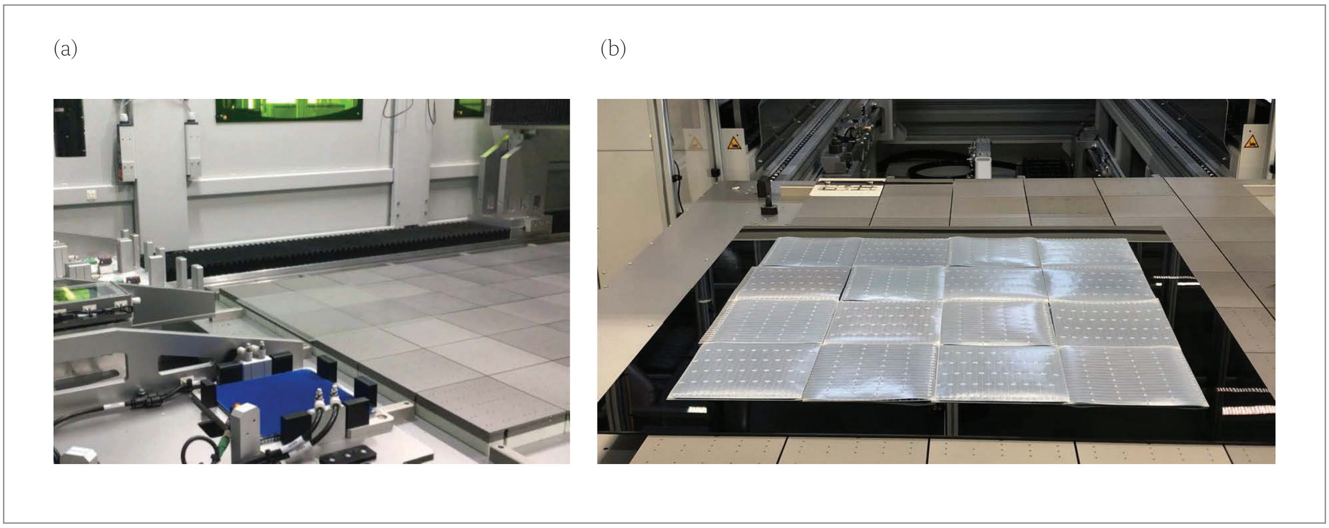

Figure 12. (a) IPTE automated lay-up station. (b) 4×4-cell module after lay-up.

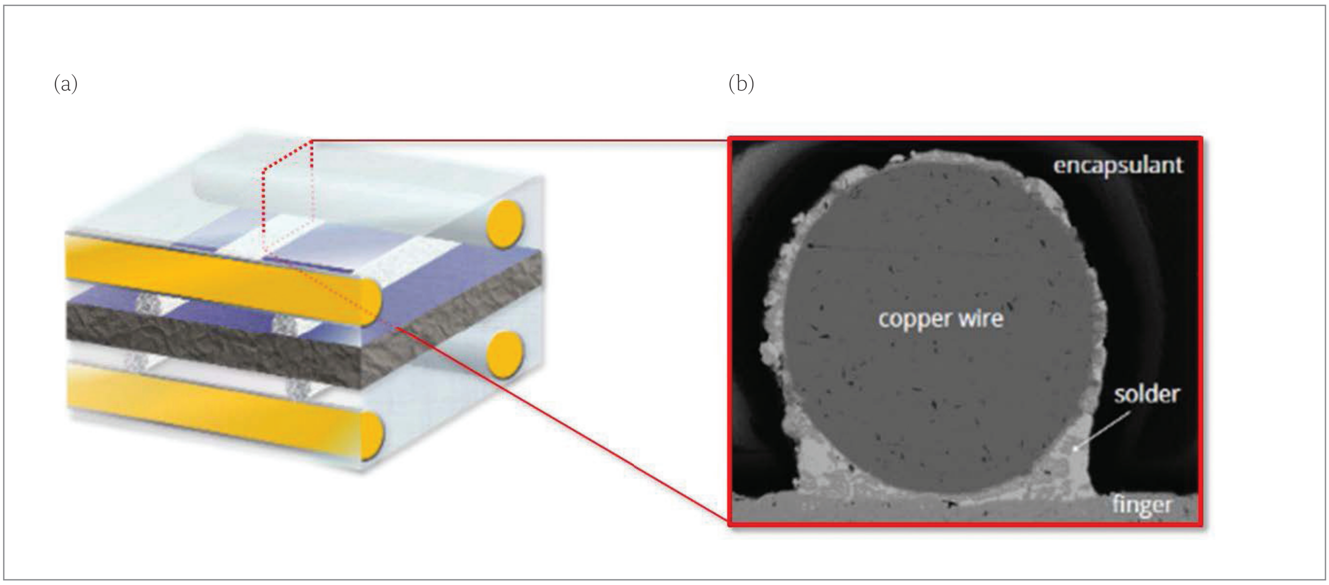

Figure 13. Schematic view (a) and cross-sectional SEM image (b) of a solder joint, created after lamination.

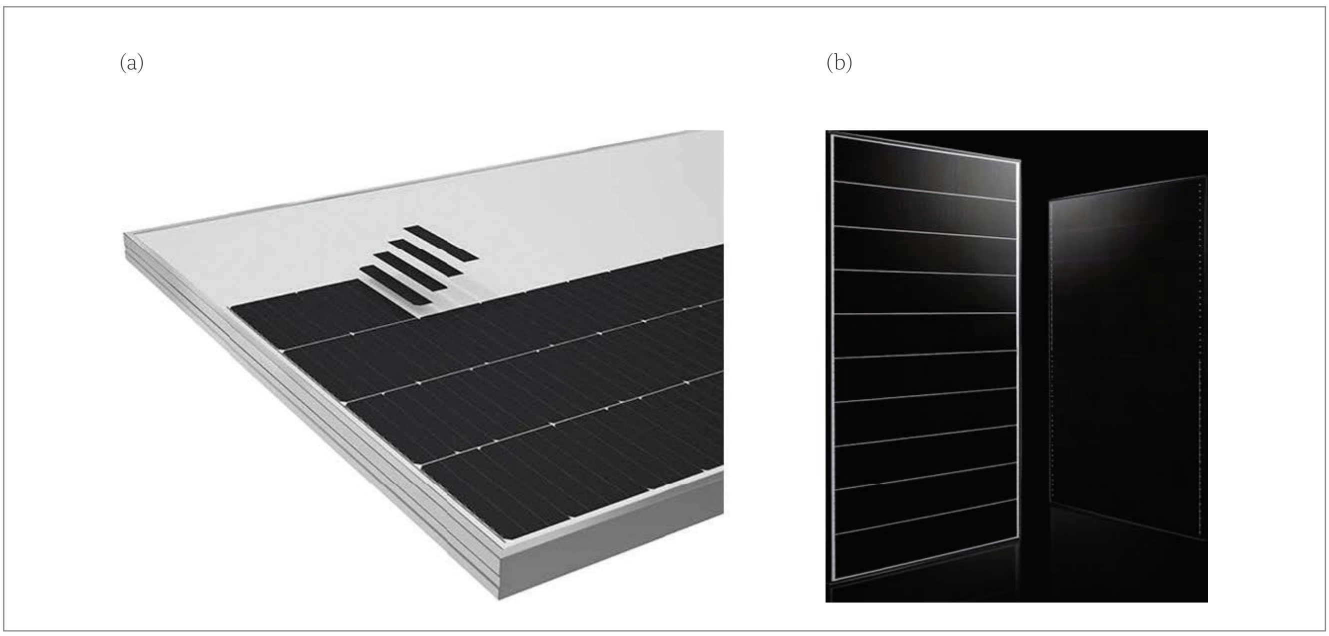

Figure 14. (a) Shingling concept (SunPower). (b) Example of a (monofacial) shingled module (Seraphim Energy).

module, but at the cost of the overlapping Si area that is lost on the bottom cell stripe.

Current shingling technologies use ECA on the collection points of the cell metallization for front-to-back cell interconnection. Although solder paste is also judged to be a possible joint material, additional measures are necessary to limit the shear forces on the solder joint because of the brittle nature of the joint.

The shingling approach leads to lower interconnection losses. As a result of the overlapping of the cells in a string, the only spaces existing between the cells is foreseen to be those between cell rows. A cell-to-module analysis comparison between a standard 6BB module and a shingled-cell module using cells cut into six strips reveals a cell-to-module (CTM) efficiency gain of 1.5–2% for the shingled-cell approach [15].

Back-contact bifacial interconnection technology?

Somewhat less obvious is the fact that back-contact cells may also be designed to benefit from bifaciality. Of course, the interconnection and module technology should then also be designed to allow the highest potential. While some technologies, for example the conductive backsheet approach [16], are less suitable in this respect, the more traditional tabbing–stringing-style interconnection, combined with an interdigitated back-side metallization, may still show potential [17], while an edge-stringing approach would require narrower stripes, more along the lines of shingling, to allow narrower fingers (and thus reduced shading). Two concepts in development that are distinctly different from such approaches, but showing significant promise, are discussed below.

Multi-ribbon

In an effort to further elaborate its multi-wire and bifacial two-side contacted technology mentioned earlier, imec has also proposed a back-contact version, using a 3D-woven fabric with added functionalities

"There is no reason why shingling could not be employed in a bifacial application with a suitable metal grid design on both sides of the bifacial cells."

[14,18]. The resulting sheet is an advanced monolithic contact sheet, combining a transparent back-side encapsulant sheet and two layers of metallic ribbons, perpendicularly oriented to each other, and interwoven with the encapsulant sheet (Fig. 15).

In addition to its function as a filling encapsulant material during vacuum lamination, the encapsulation material is used as an electrical insulator material between opposing polarities on cells and conductive ribbons, where needed, to avoid shunting. The result after lamination resembles a multi-layer PCB.

The concept itself is based on a hybrid twill-weave-style fabric, a variant of a simple plain weave, and consists of interwoven metal and polymer ribbons. The polymer ribbons are multi-functional: they act as encapsulation material and simultaneously ensure electrical insulation where necessary. The two layers of metal ribbons cross each other according to a specific scheme, determined by the weaving style.

Depending on the location in the 3D fabric, the crossing metal ribbons are either separated by the encapsulant ribbon to allow electrical insulation, or electrically making contact at the locations where the ribbons cross each other on the same side of the encapsulant ribbon to create a floating interweaving interconnection. The metal ribbon layer on the cell contact (bottom) side of the 3D-contact sheet locally protrudes to allow an interconnection with the individual cell fingers of the same polarity on the cell. As such, these ribbons replace the busbar metallization on the cell. The second layer of busbars in the fabric is used to create an electrical connection between subsequent cells in the module for connection in series. The principle is schematically illustrated in Fig. 16.

Using only encapsulation material and metal

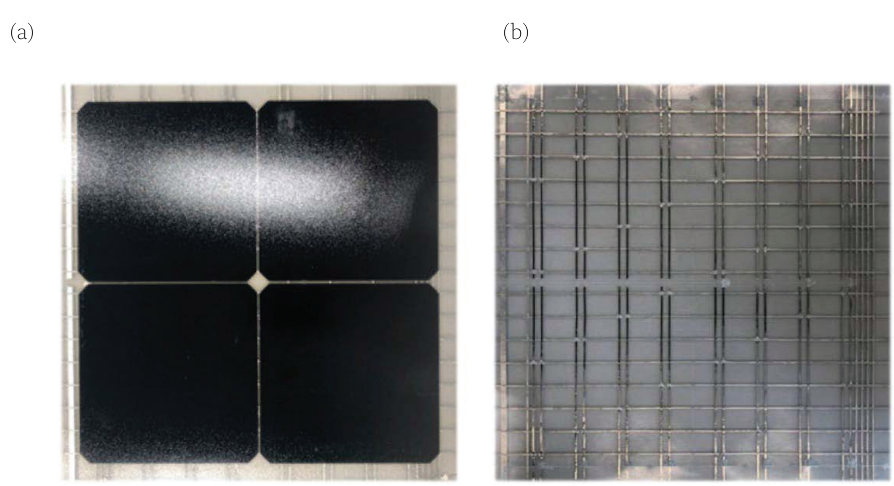

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Figure 15. (a) 3D-sheet-contacted module incorporating four IBC cells. (b) 3D interconnection sheet.

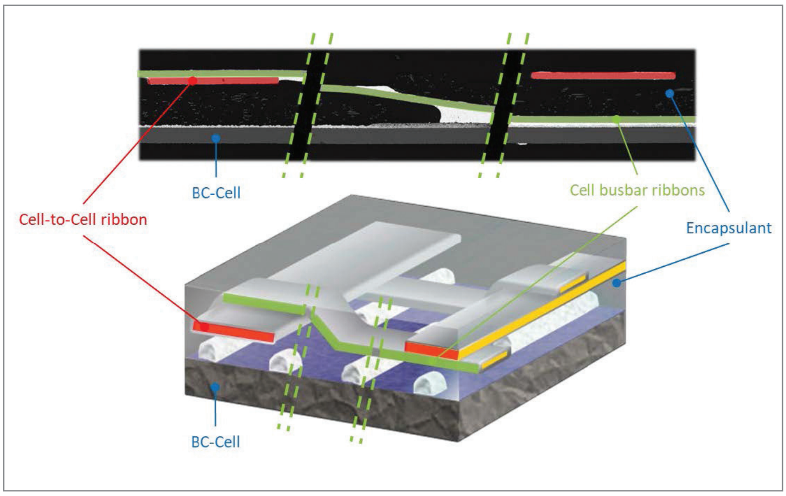

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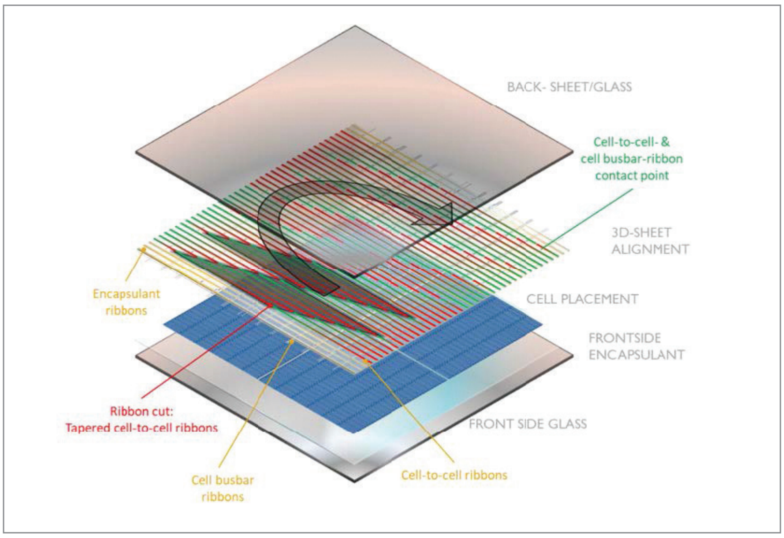
Figure 16. 3D drawing of an interconnected cell (bottom), and cross-sectional images of different contact configurations (top).



Source: imec

Figure 17. Exploded view of a 3D-fabric-interconnected module incorporating four bifacial IBC cells.

ribbons, both of which ensure structural integrity, the interconnecting foil also provides enough encapsulation material for good lamination of the cells and backsheet without compromising the electrical separation of the different conductors (Fig. 17).

The double function of the encapsulant, combined with the creative tapered ribbon structure, results in an interesting cost perspective. With the use of a tapered cutting structure of the cell-to-cell busbars, a copper reduction of 37% is achieved for a 60-cell-module with 3D interconnection (with six sub-cell metallization design), compared with standard 5BB modules, while still maintaining a total cell-to-cell interconnection conductor cross section similar to that of a non-tapered ribbon interconnection approach. Eliminating the solder coating on the cell-to-cell busbars results in a total solder-to-copper ratio equal to that of a 5BB module. Potentially, the cell cost can be reduced, since no additional insulating material on the cell is required because this function is accomplished by the rear-side-integrated encapsulant.

"With the use of a tapered cutting structure of the cell-to-cell busbars, a copper reduction of 37% is achieved for a 60-cell-module with 3D interconnection, compared with standard 5BB modules."

SWCT approach for back-contact HJT cells

Building further on the SWCT multi-wire technology for bifacial interconnection, Meyer Burger together with CSEM have demonstrated a further development of SWCT technology, adapting it for back-contact interconnection of bifacial heterojunction solar cells (Fig. 18).

By using dedicated wires for both terminals of the back-contact cells, on a single contact foil, along with interruptions of the wires in dedicated locations, a series interconnection can be created between the solar cells in a cell string. As described previously, electrical solder interconnection of the fingers of each polarity with the dedicated wires is created during the subsequent vacuum cycle. This interconnection principle was demonstrated and presented by CSEM at the 2019 EU PVSEC conference [19]. In this case, the insulation between cell fingers and wires of opposing polarities above the cell is realized by printing an additional insulating layer on the cell.

Conclusion

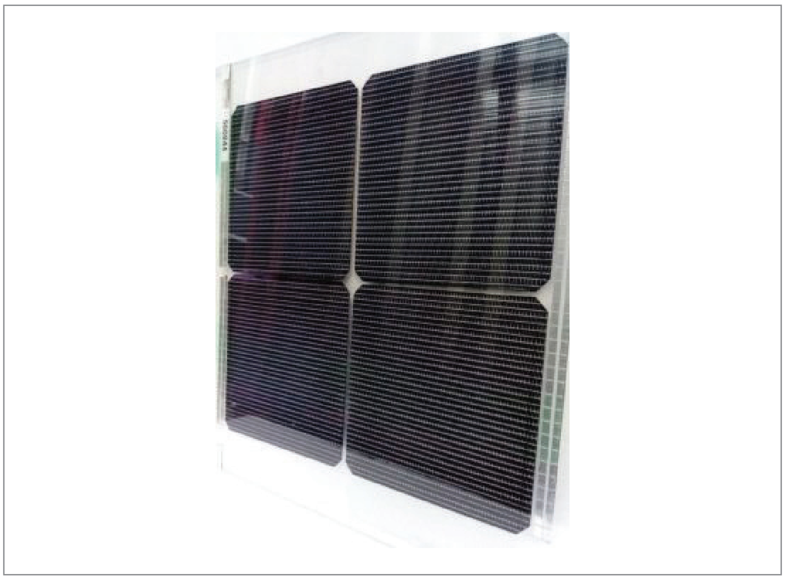
This overview has highlighted the fact that several bifacial technologies for two-side contacted cells are beginning to win a share of the PV market and that suitable interconnection technologies are being deployed to this end, while offering a glimpse of the possibilities for back-contact cells.

Starting from the transformation of solar cells into bifacial cells, and providing this transformation with suitable interconnection technologies, an important takeaway is that the subsequent implementation must not negate these efforts. In practical and chronological terms, this means that the positioning and dimensioning of bussing ribbons, junction boxes and frames, as well as any support structures or other obstacles that are deployed at the installation site, should be very carefully considered in order to minimize potential shading of the rear side.

Acknowledgements

The authors gratefully acknowledge imec's SiPV industrial affiliation programme and its partners. Part of this work was conducted within the framework of the TWILL-BIPV project, co-financed by imec.ICON, and with project support from Flanders' Agency for Innovation and Entrepreneurship. The work was also partially funded by the European Union's Horizon 2020 programme for co-financing research, technological development and demonstration projects, under Grant Agreement No. 727523 (NextBase) and No. 857793 (HighLite).

The authors would also like to thank R.V. Dyck, G. Doumen, L. Vastmans, N. Andries, P. Meyers and R. Moors for their valuable contributions.



Source: NextBase

Figure 18. Module interconnected with dedicated SWCT foils for BC-HJT cells.

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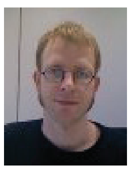
Tom Borgers joined imec in 2000, working on III-V IR detector technologies, flip-chip development for megapixel arrays, and microsystems 3D integration and packaging. Switching to the field of PV in 2008, he became involved in back-contact solar cell interconnection concepts. In 2012 he joined imec's Reliability and Modelling group and is currently working on module interconnection technology with the PV Module Technology team.



Jonathan Govaerts received his Ph.D. from Ghent University, Belgium, in 2009 on packaging and interconnection technology for (flexible) electronics. Since then he has been working with the Solar Cell Technology group at imec, focusing on cell-module integration of silicon solar cells.

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