Back-contact technology: Will we need it in the future?

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ABSTRACT

The back-contact (BC) technology currently available on the market is considered to be either highly efficient but extremely expensive (interdigitated back contact – IBC – from SunPower) or, if cost-effective, not very efficient (metal wrap-through – MWT) compared with what is becoming today's new standard: passivated emitter and rear contact (PERC) technology. Something in between, such as low-cost, high-efficiency IBC cells and modules, would therefore be desirable. This paper briefly describes the past, focuses on the present, and forecasts the possible future developments of BC technology in respect of efficiencies, costs and applications.

Introduction

"Which will win?" is a frequently asked question at PV conferences and workshops. "Which will win – thin film, c-Si, p-type, n-type, bifacial, HIT, back contact, screen printing, plating, diamond wire, slurry...?" This is a complex question, the answer to which can only be guessed; some predicted answers to this most important question are given in, for example, the ITRPV [1]. What is known for certain, however, is that of all energy sources, PV will definitely be the winner, which is what Bloomberg has already forecast in their fairly recent study "Energy Outlook 2015" [2]. From 2022 onwards, PV will be the most important energy source in terms of the largest yearly added capacity (around 100GWp/year), with a yearly energy production of 1,040TWh at a cost of, on average, €0.05–0.06/kWh. And with this, the other, more detailed, questions will be easily answered. Even PV niche markets with 10–15% contribution will win, as they will still represent a market of at least 10–15GWp per year.

The geographical technology spread of c-Si manufacturing is quite clear. On the one hand there is China, with standard Al back-surface field (Al-BSF – mostly multicrystalline) p-type technology; on the other there is the rest of the world (ROW), with more advanced technologies, such as (at the moment) passivated emitter and rear contact (PERC), passivated emitter rear totally diffused (PERT), heterojunction (HJ) and interdigitated back contact (IBC). In the coming years China will progressively move to PERC as well, which will become standard in the next five to seven years, whereas ROW (including Taiwan, Korea and Japan) will implement in addition more and more advanced technologies, such as bifacial PERT, HJ and IBC. PV Tech also states that there is a "continued push from a diverse range of cell architectures, with no sign of any significant push to consolidation across the different n-type or p-type, mono or multi, and standard or advanced cell processes being used in production today" [3].

This paper presents a review of back-contact (BC) technology and gives a prediction of which role this technology will play in the future PV market.

> "The very first solar cell, created by Bell Labs in 1954, was actually an n-type BC solar cell."

A short history of back-contact cell and module technology

The very first solar cell, created by Bell Labs in 1954, was actually an n-type BC solar cell [4]. Two decades later, SunPower went into production with a 4-inch IBC solar cell, followed by a 5-inch version. The module assembly was then, and still is today, kept very simple, as the IBC cells are soldered at the edges. Around the year 2000, ECN came up with the 'PUM cell' concept, which was a metal wrap-through (MWT) cell and which also had the front (emitter) connected to the rear side. Standard stringing was not possible at the time, as that technology resulted in a significant bowing of the devices; a new module technology therefore had to be developed.

ECN, Solland and Eurotron were the first to develop the conductive backsheet (CBS) technology for PV, whereby the BC cells are picked and placed on a Cu backsheet. Solland was still focusing on soldering, whereas Eurotron and ECN were using conductive adhesive materials. The current cell technology then was based on mc-Si MWT, and many companies, such as Photovoltec, Sunways and others, had developed their own particular versions. At that time, around 2005, there were a few companies with MWT cells on the market, but hardly any reliable BC module technology existed. This was also the period when selective emitters and PERC technology were slowly penetrating the PV market, and so the advantage of MWT cells was getting smaller and smaller. Yingli together with ECN were developing an n-type version of MWT as well, but it quickly became clear that PERC and nPERT were becoming too powerful and the advantage of nMWT too small.

Today, however, the situation has reversed: there are many module technologies on offer for BC solar cells (see the module section discussion), but there are very few manufacturers producing this type of cell. The only feasible way of launching BC technology on the market is by means of a cost-effective IBC technology in conjunction with a simple module manufacturing process, which will be discussed in this paper.

Many PV experts say that BC technology does not, and will not in the future, demonstrate any benefit compared with two-side-contacted technologies: this is because of progressively thinner fingers and more favourable cell-to-module (CTM) P_{mpp} gains, so that the advantage of no shadowing on the front will become too small to justify the higher process complexity. However, the ITRPV roadmap still forecasts a 2%abs higher efficiency in 2026 for IBC technologies compared with other technologies, as well as a market share of more than 10%, which will equate to around 12GWp/year volume at that time (see Fig. 1).

The reason for this 10% market share is not only the high forecast efficiency

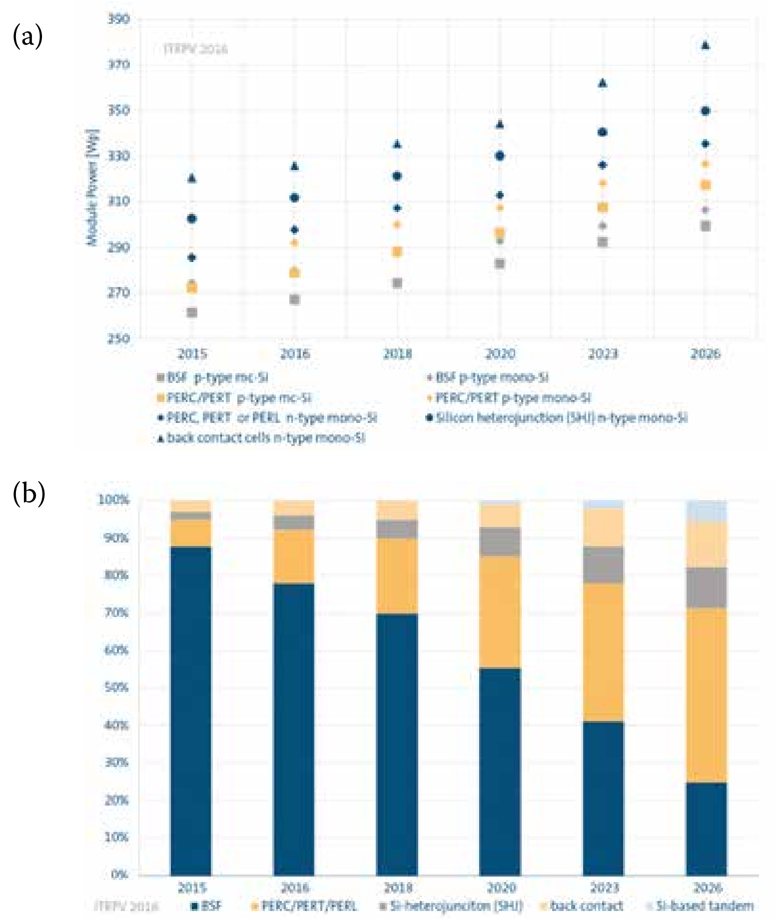

Figure 1. (a) Efficiency forecast for different technologies; (b) corresponding market shares. (Source ITRPV [1])

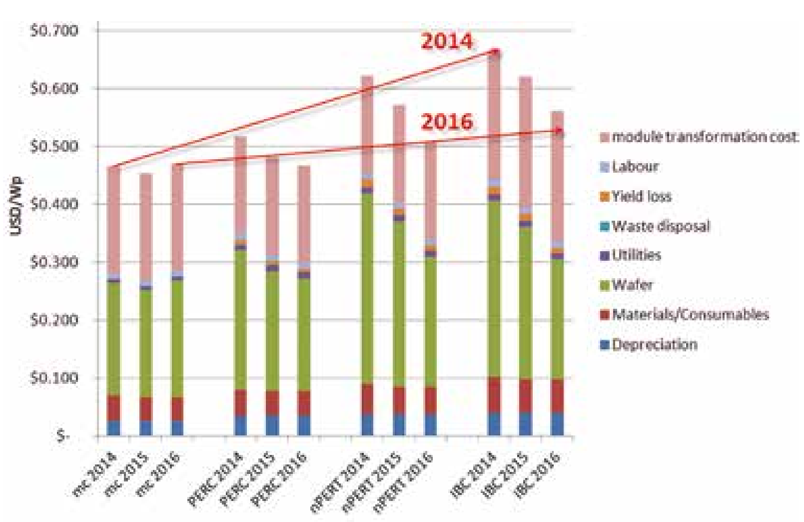

Figure 2. COOs for different low-cost c-Si technologies.

but also the advantages such as:

- Perfect front-side module homogeneity (no metal contacts on the front).
- Simple process for different colours (no contact firing through a black or coloured layer needed).
- Single print step for metallization (if appropriate paste is used).
- Simple process for passivated contacts (all passivated contacts on the back).
- Simple interconnection and better yield for thin cells (picking and placing of cells on a conductive backsheet instead of stringing).
- Higher shadowing tolerance (since an IBC cell can itself act as a bypass diode).

In the authors' opinion the IBC solar cell and module technology will have at least a niche market in the future for rooftops and building integration in, for example, the EU, Japan and the USA. These niche markets will, however, be huge and will gain in importance as time goes on.

Time for monofacial c-Si

For many decades mc-Si technology has dominated the market because of the much lower cost of the mc-Si wafers. In around 2005, however, mc-Si wafer producers started to increase the directional solidification quality by the introduction of seed crystals at the bottom of the crucible. This is when the so-called *quasi-mono* wafers first started to gain interest on the PV market; however, scientists began to realize quite quickly that it is not the crystal size but rather the dislocation density that is the more important for mc-Si wafer quality. On the contrary, the grains have to be small and not large: Taiwanese scientists were the first to discover that small crystals have fewer dislocations, and the technology of high-performance (HP) mc-Si material started to develop. As the HP material also uses seed crystals, and the crystallization is slower than for standard directionally solidified mc-Si wafers, the costs in this case are slightly increased as well. On the other hand, the costs for Cz-Si crystallization are lower, and for the first time, in 2016, we are in a situation where the wafer prices for mc-Si and Cz-Si are the same. This has the consequence that, again for the first time, PERC Cz-Si modules show similar (or even lower) manufacturing costs per Wp than standard mc-Si Al-BSF modules.

This can be seen in Fig. 2, in which the cost of ownership (COO) for different module technologies is summarized. The COO is calculated for an Asian production site with 100MW capacity only. It can be clearly seen that the major difference in costs per Wp when comparing different technologies are hidden in the wafer costs (green bars). In the past, when mc-Si wafer costs were much lower than those of p-type and n-type Cz-Si, the lowest costs per Wp were claimed by the standard Al-BSF module. This is now changing in favour of Cz-Si technologies, and is even more apparent when the levelized cost of electricity (LCOE) is considered, as will be seen in the next section.

Time for high-efficiency technology

Fig. 3 shows the corresponding LCOEs for the different technologies depicted in Fig. 2. At the system level, the higher costs for high-power devices are recovered by the lower BOS costs, because the higher the module power is, the lower the balance of system (BOS) costs are.

If we think in terms of cost/Wp, the high-efficiency devices PERC, nPERT and IBC are getting closer and closer to mc-Si modules, as the wafer costs for mono c-Si devices are approaching those for mc-Si. As regards cost/kWh, some mono c-Si technologies are more cost-effective than mc-Si technology. If bifaciality is considered, the LCOE can be reduced to a level never reached before.

Time for back-contact solar cells?

Several different BC technologies have in the past been considered to be of interest to the PV market, namely metal wrap-around (MWA), MWT, emitter wrap-through (EWT) and IBC. In this section the geometries, as well as the advantages and disadvantages, of all these concepts will be described.

First, the geometries of MWA, MWT and EWT cells are shown in Fig. 4 [5]. Of these, the **MWA** cell (Fig. 4(a)) is the simplest – however, the cell needs to be cut into pieces, as the busbars are located only on the edges. At the time of its conception, MWA was not considered to be an attractive option, because of the low scalability of the solar cell. Today, however, with a new awareness of using 1/2, and even 1/3 or 1/4, stripes of 6-inch cells in order to lower the CTM resistive losses, the MWA cell could be appealing for the shingling technique, which is currently growing in popularity. Many companies (e.g. Solar City and SunPower) are now working on shingling instead of stringing.

MWT technology requires the least effort to use 6-inch solar cells and to realize a contact on the rear side of the cell. Two different approaches have been used: one by ECN and Solland, and the other by Photovoltec and Sunways. The first consortium used 16 larger holes with unit cells around these holes in the form of an organic structure, whereas the others used the standard H-pattern cell structure with several holes for each rear busbar. This technology was developed for p-type mc-Si as well as for Cz-Si wafers: however, it quickly became evident that the upcoming technologies, such as PERC and PERT, would surpass the advantage of MWT. Yingli started to adapt n-type MWT technology from ECN as well, but with little success. It is now commonly accepted that if a BC cell should come on the market, it would have to be an IBC one.

Advent Solar and a few other companies have tried to introduce

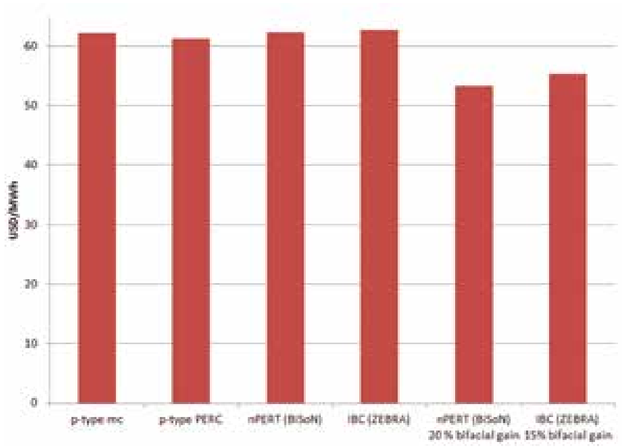

Figure 3. LCOE for different low-cost c-Si technologies in 2016 for southern Spain (yearly global horizontal irradiation = 1,800kWh/m²).

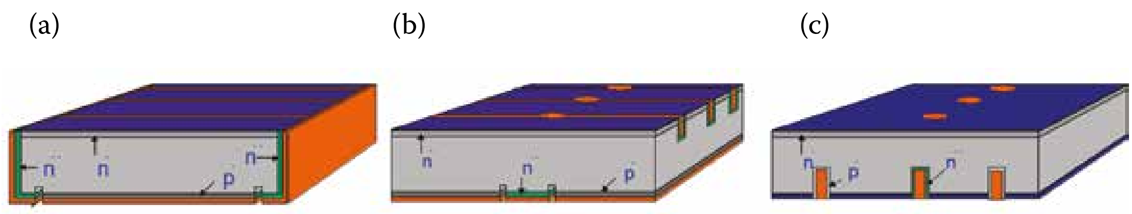

Figure 4. Different BC concepts: (a) MWA, (b) MWT, and (c) EWT [5].

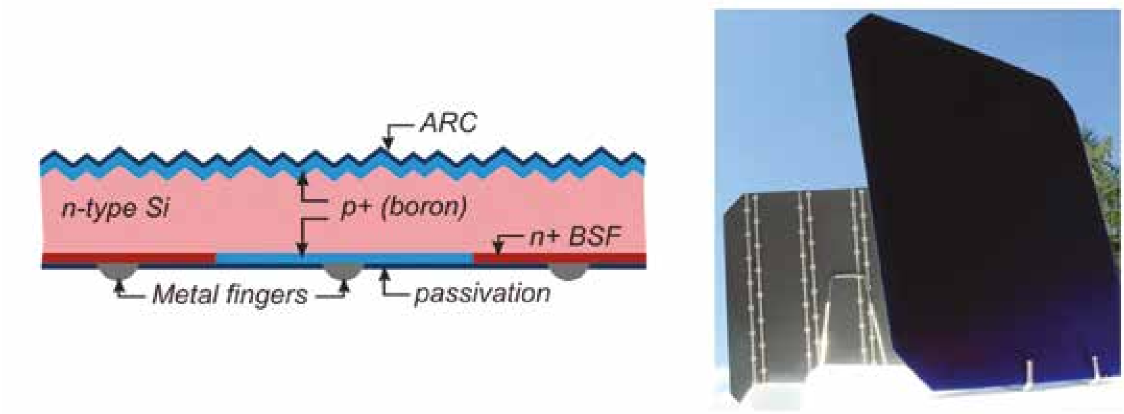

Figure 5. The ZEBRA IBC concept.

Company/Institute	Area [cm²]	Efficiency [%]	Process	Reference
Sharp	4	25.1	SHJ-IBC	[6]
ANU	4	24.4		[7]
ISFH	4	23.4	Implanted	[8]
imec	4	23.3	Diffused, evaporated	[9]
ipv Stuttgart	4	23.2	Laser doped	[10]
FhG ISE	4	23.0		[11]
Panasonic	156	25.6	SHJ-IBC	[12]
SunPower	121	25.2	Diffused, plated	[13]
Trina Solar	239	23.5	Diffused, SP	[14]
imec	239	22.7	Diffused, evaporated	[15]
Samsung	155	22.4	Implanted, SP	[16]
Bosch	239	22.1	Implanted, SP	[17]
ISC Konstanz	239	22.0	ZEBRA, diffused FFE, SP	[18]
ipv Stuttgart	156	21.9	Laser doped, SP	[19]
ECN	239	21.3	MERCURY, diffused FFE, SP	[20]
DuPont	239	21.3	Paste diffused FSF, SP	[21]
Hareon	239	19.6	Diffused FSF, SP	[22]

Table 1. Different IBC technologies on small and large areas (SP=screen printed, FFE=front floating emitter, FSF=front-surface field, SHJ=silicon heterojunction).

EWT to the market. This technology has no front metallization at all. The carriers collected on the front emitter are transported through the emitter to the back contact; therefore, thousands of holes are needed, which is a complicated process and results in a fragile device.

IBC technology, which is illustrated schematically in Fig. 5 for the ZEBRA IBC concept, became available on the market many years ago from SunPower, and a number of other companies have since tried to simplify this technology.

Table 1 summarizes the different IBC technologies from different companies and R&D labs, and the efficiencies achieved on small and large areas. Not only do the small- and large-area capabilities make a difference, but also the costs associated with the processes are an important factor.

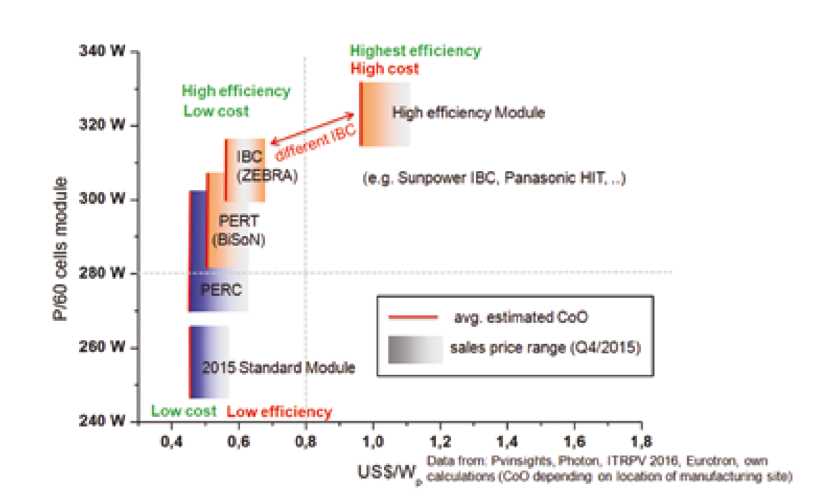

Figure 6. COOs for different low-cost (left) and high-efficiency (top right) technologies.

> "The highest efficiency modules no longer justify the high costs, as the gap in efficiency in mass production with the low-cost solar cells is gradually closing."

The COOs of the different technologies in Fig. 2 are illustrated in a different way in Fig. 6: this alternative representation depicts not only the costs and selling process, but also the attainable power for a module incorporating 60 6-inch solar cells. Two different regions can clearly be seen: 1) low cost and high efficiency (upper left); and 2) high cost and highest efficiency (upper right). The highest efficiency modules no longer justify the high costs, as the gap in efficiency in mass production between them and the low-cost modules is gradually closing.

By way of example, for *cost-effective IBC solar cells* the ZEBRA concept, which is currently being developed within ISC Konstanz's HERCULES FP7 EU project [23], will be described next. In this project it is proposed to develop innovative n-type monocrystalline c-Si device structures based on two-side-contacted (SHJ) and back-contacted (IBC) solar cells with alternative junction formation, as well as hybrid concepts (homo-heterojunctions). These concepts have been identified as the most promising technologies for achieving ultra-high efficiencies using industrially relevant processes. The HERCULES strategy is to transfer the developed processes to an industrial scale by considering all the major cost drivers of the entire manufacturing process chain. The final objective is to obtain both high-efficiency solar cells and modules using adequately simple process sequences.

Within the HERCULES project, ISC Konstanz is further improving and industrially piloting its low-cost and high-efficiency ZEBRA technology. Industrially available techniques for mass production – such as conventional diffusion processes, PECVD deposition, and screen printing and firing-through metallization – are used in the fabrication process for the ZEBRA cell concept. Moreover, the concept features a front floating emitter, which significantly improves carrier-collection efficiency for device geometries with large pitch and base regions. (See Fig. 5 for a schematic cross-section of the ZEBRA cell concept, together with an actual photograph of the prototype solar cell.) The best ZEBRA cell fabricated so far on a large-area substrate has an efficiency of 22%; in pilot line production, an average efficiency of 21.5% was demonstrated.

Additionally, as a result of their open rear-side metallization grid, the ZEBRA cells are bifacial; this allows the fabrication of bifacial modules, which could significantly boost the energy yield as compared with cells having a fully covered rear side. ISC Konstanz has demonstrated that such a bifacial module would typically generate an energy yield 15% greater than that of a module with similar cells but monofacial [24]. This is significant because it also means that – if installed in a suitable manner (i.e. ground mounted) – such a bifacial module (with about 300Wp) would produce an energy yield similar to that of the currently best-performing SunPower module (with 345Wp) fabricated with 24%-efficiency cells.

Back-contact modules

The module integration of BC cells at an industrial level is mainly realized by variations of two current technologies: 1) specially adapted tabber–stringer tools, with which the cell–cell contact is established by soldering or conductive adhesive gluing of ribbons; and 2) the CBS approach, where BC cells are glued on top of a conductive metal foil covering the full rear side of the module and structured to provide cell–cell interconnections as well as string interconnections.

Apart from these two solutions, few other industrial module concepts seem to be adaptable to the integration of BC cells, although many new approaches are being investigated by R&D teams all over the world.

Back-contact modules based on tabbing/stringing

The traditional approach used for BC module assembly is the single-sided tabbing/stringing method. The contact between the BC cell and the ribbon can be realized by soldering, electrically conductive adhesive (ECA), or solder paste. In the case of MWT, only point contacts between cell and ribbon are possible; an isolation layer must be introduced locally to avoid electrical contact between a ribbon of one polarity and the cell metallization of the opposite polarity, which would cause a short circuit of the cell. For IBC cells like the ZEBRA cell featuring floating busbars on its rear, this isolation is not needed, and soldering on the full length of the busbars can be realized.

Single-sided ribbon interconnection inflicts high mechanical stress on the solar cell, because this stress is not counterbalanced from the other side. That is the reason why either structured or super-soft ribbon is used to minimize the mechanical stress and hence reduce the bowing. An important advantage of ribbon interconnections compared with CBS is the possibility of assembling a bifacial module by either using a transparent backsheet or assembling a glass–glass module. In this case the bifaciality of back-contacted cells, such as the ZEBRA cell, can also be exploited at the module level, leading to a significant increase in energy yield (kWh/kWp(front)) and thus to a reduced LCOE (€/kWh).

Dedicated equipment for the stringing of BC solar cells with several (up to eight) rear busbars is available on the market from various companies (e.g. Teamtechnik or Somont) and is already being used to produce MWT modules. There are also bespoke solutions on offer, such as the Soltech approach developed in-house; this is based on point-contact stringing of ribbons along the entire cell length (see Fig. 7) through a porous glass fibre sheet which provides electrical insulation.

Another solution for tabbing-based interconnection is edge stringing, as used by SunPower; here, the electrical string current is transported by the cell's metallization. The cell–cell interconnection tabs are located in

Figure 7. Back-contact stringer: MWT cells are interconnected with stress-relieved ribbons using solder paste; a glass fibre sheet between the cell and the ribbons prevents short circuits. (Source: Soltech, MWT WS 2013 Freiburg)

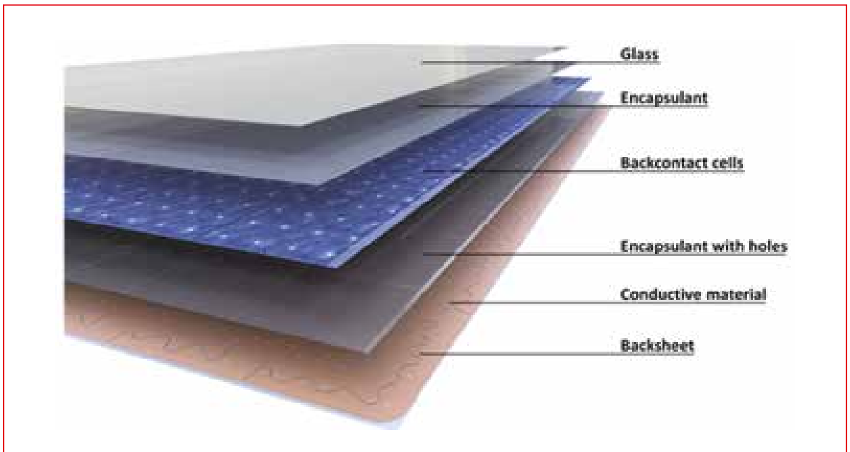

Figure 8. A typical module sandwich for CBS-based modules. (Source: Eurotron)

PV Modules

between the cells, contacting only dedicated pads at the cell edges. The advantage of this method is that the mechanical stress inflicted on the solar cells is much reduced; a limitation, however, is the resistive losses in the cell metallization, which scale with cell size, and thus the maximum cell size is restricted to five inches.

Back-contact modules based on a CBS

The CBS approach was adopted from printed-circuit board production and is only suited to BC cells. It was developed by ECN, TTA and Solland for p-type MWT solar cells, and introduced to the market in 2009 by Eurotron, a daughter company of TTA. Other providers of technology and equipment for module assembly based on CBS are the Italian company Formula E and the Finnish company ValoE. At the moment, only Eurotron's equipment is used in industrial module production by a few companies producing MWT modules (to the authors' knowledge, the most powerful MWT module, generating a power output of 300W, is produced by Nanjing Sunport Power Co. Ltd).

A typical module sandwich including the CBS is composed of glass, front encapsulant, BC cells, rear encapsulant with local openings to electrically contact the cells, and the CBS (see Fig. 8).

The conductive layer, which is the basis of each type of CBS, is around 35µm thick (depending on the supplier), with a total weight per cell area of more than twice the mass of the ribbon needed to interconnect a three-busbar cell. This results in a very low series resistance related to the P_{mpp} CTM losses. The CBS is mostly made of copper or of aluminium coated with a thin layer of copper to aid contact (e.g. Hanita Coatings' DuraShield). The metal covers almost the entire module area and is only interrupted by small isolating trenches, which define conduction paths for both polarities. These isolation trenches are formed by mechanical milling, by laser or by wet chemical etching. To avoid corrosion the copper layer requires a suitable finish, such as ZnCr (e.g. Krempel's AKACON BCF) or treatment with an organic surface protectant (OSP – e.g. Isovoltaic's Icosolar TPC 3480) on the side facing the solar cells.

For most CBS concepts the rear encapsulant provides electrical isolation between the CBS and the cell; the encapsulant is locally opened by mechanical punching or laser. The typical CBS also includes a stack of polyethylene terephthalate (PET) and Tedlar (or similar material) on the rear side to protect against environmental influences. The EBfoil BYS, developed by EBfoil and produced by Coveme, even goes one step further: this is a stack system consisting of a rear encapsulant with a dielectric layer combined with a CBS composed of PET layers, a copper or aluminium conductive layer, and a primer layer. After structuring the two components according to the desired module circuit design, the stack is used as a single sheet that combines the CBS and the rear-side encapsulant. Other concepts, such as 'contacfoil-connect' by Eppstein Technologies, consist of simply a structured copper sheet and a dielectric layer for electrical isolation between cell and copper, which is locally opened by laser. In the module assembly process, the rear encapsulant is placed behind the CBS, followed by a standard backsheet or Eppstein's 'contacfoil-back'.

The electrical contact between BC cells and the CBS is accomplished by ECAs, although solder paste can be a cheaper alternative. In both cases the conductive ink is applied locally onto the CBS or the rear side of the cell by stencil printing or dispensing during module assembly. The printing image matches the openings in the isolation layer to allow contact formation. The BC cells have to be placed precisely on top of the rear module stack using a pick-and-place unit. ECA gluing or the use of solder paste introduces very low mechanical stress compared with soldering. Usually, after cell placing the finished sandwich is flipped before lamination. During lamination the low ohmic electrical contact between the cell and the CBS is established. One drawback of this contacting procedure is that no electroluminescence (EL) inspection of modules prior to lamination is possible.

Using the above-mentioned methods, ISC Konstanz and Eurotron collaborated to adapt the MWT module technology to fit the needs of the ZEBRA back-contact back-junction cell within the framework of the HERCULES project, which has received funding from the European Union's 7th Framework Programme for Research and Technological Development under Grant No. 608489. The first prototype back-contact module comprising 60 ZEBRA cells was assembled in Q3 2015 and featured a 300Wp power output, as shown in Fig. 9. This result demonstrates the potential of a concept which yields an initial power level that common technologies can only get close to because of their physical limitations.

Other methods for back-contact module assembly

Although many alternative approaches for assembling BC modules have been investigated by various research centres and R&D teams around the world, most do not go beyond the mini-module level. Some interesting concepts are listed below, without claiming to be complete.

In a publicly funded project called InGrid (No. SOLARERANET2-093, Grant No. 325821), for example, ISC Konstanz in a consortium with STRE, Prodintec and Gwent investigated a BC module solution based on printing an interconnection circuit directly on top of

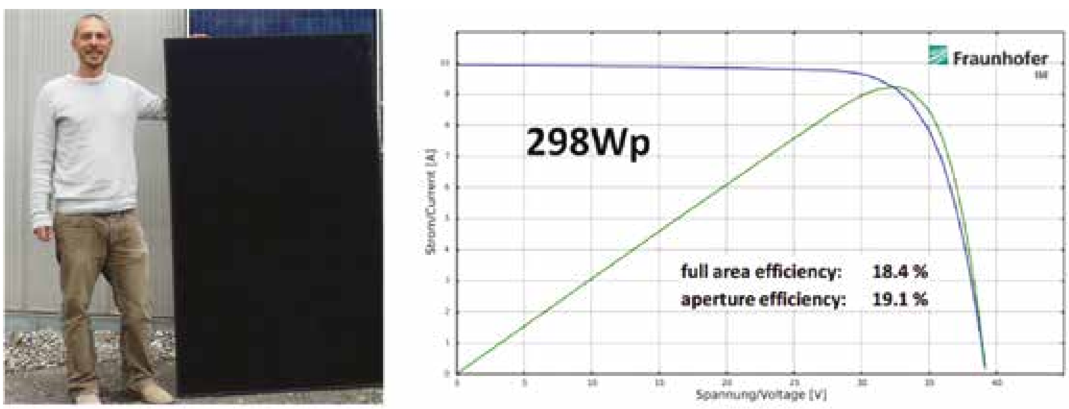

Figure 9. ZEBRA Eurotron Module certified at FhG ISE CalLab. The second-best module was sent for certification.

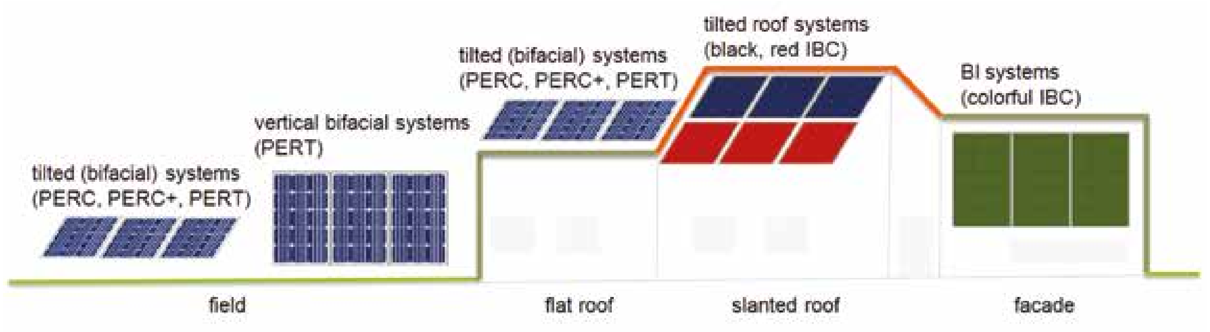

Figure 10. Split for (bifacial) PERT (and PERC+) and IBC (and PERC) applications.

the rear encapsulation layer, which would dramatically simplify the module assembly.

Together with Soltech, imec developed a method they call *woven fabric interconnection*. This fabric is a compound material in which thin metal wires and glass fibres are arranged in such a way that cells can be interconnected by the metal wires, while the glass fibres provide electrical isolation where needed.

Concepts such as the NICE module developed by Apollon Solar and Fraunhofer ISE's TPedge technology are well suited to BC module assembly. In both cases the lamination step is replaced by edge sealing of two glass sheets after placing cell strings inside. Fraunhofer ISE installed 70 TPedge modules fabricated in-house with MWT cells on the facade of its lab building in 2015. NICE technology is already used industrially for two-side-contacted cells, but it is also particularly attractive for BC modules incorporating cells with continuous busbars. The electrical cell ribbon contact is established during module assembly solely by mechanical pressure, and thus cell bowing does not occur. In addition, the multi-busbar concept offered by Schmid could be adapted to BC solar cells, provided that the alignment precision of the single wires is sufficiently high.

Back-contact module applications and markets

As already discussed, the applications for BC modules will be found in sectors where more than just electricity generation will play a role; these will be mostly on houses and on building facades. For slanted rooftop applications, black modules will be used; if a roof with red tiles is to be electrified, even reddish modules could be applied. The markets for this are the EU (e.g. the Netherlands is a pure rooftop market), Japan, Australia and the USA.

For the building-integration sector, facades could be equipped with pleasing, colourful modules, and even hybrid modules (electricity and hot water) are under development. As the BC modules use a CBS, the temperature coupling to the solar thermal application on the rear is very effective. BC modules can even be made bifacial: this could be an advantage when, for example, the aesthetics of the system are also important, such as in a flat roof installation.

Fig. 10 summarizes schematically what has been discussed above. On the left side of the image, the major application of PV in large systems using cost-effective PERC, PERC+ and PERT modules can be seen. As regards the building sector (right side of image), aesthetics and small-area requirements (high efficiency) will play a role, which means more and more BC modules will penetrate this particular market.

> "The authors are convinced that low-cost IBC cell and module technology will play an important role and assume a strong market position in the future."

Summary

PV technology has a bright future – there is no doubt about it. The authors are convinced that low-cost IBC cell and module technology will play an important role and assume a strong market position in the future. Even though the highest-power advantage is becoming smaller and smaller, there are still a number of applications, mostly in the building segment, that make IBC technology an extremely attractive option.

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