An overview of module fabrication technologies for back-contact solar cells

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ABSTRACT

Apart from aesthetics, the gain in electrical performance of back-contact solar cells and modules is particularly attractive compared to conventional PV modules. This major benefit results from getting rid of (the majority of) the metallization at the front, and providing all the cell contacts at the back. An overview is presented here of the different concepts put forward by different institutes and companies around the world for such back-contact modules. The different types of state-of-the-art back-contact cell are first introduced, together with their corresponding contacting and interconnection schemes. Keeping in mind the reference module technology for two-side-contacted cells as a starting point, each module concept is then briefly discussed in terms of technology and level of maturity. Finally, the main technological differences are summarized.

Introduction

The conventional approach that has been widely adopted for manufacturing modules, based on two-side-contacted cells, is the one described, for example, in Wohlgemuth & Narayanan [1]. The technique consists of first interconnecting the separate cells into strings by soldering ribbons from one cell's contacts to the next (so-called 'tabbing-stringing'). The strings are then laminated between a transparent glass or polymer frontsheet and a glass, metal or polymer backsheet using the cross-linking material ethylene-vinyl acetate (EVA). This is a very mature technology, and was developed for cells requiring out-of-plane interconnection between the front of one cell and the back of the neighbouring cell. The typical process flow diagram is shown in Fig. 1.

> "The application of back-contact cell and module technology is expected to increase significantly."

However, with the drive towards higher efficiencies, several different concepts for crystalline silicon back-contact solar cells have been proposed, investigated and developed [2]. This direction of research and development is also in line with the ITRPV roadmap, where the application of back-contact cell and module technology is expected to increase significantly, both in absolute and relative terms. For such cells, it is worth questioning whether conventional module technology is still optimal and preferable.

Back-contact solar cell contacting and interconnection scheme

Current back-contact solar cells can be broadly divided into two types on the basis of the conduction mechanism for drawing the current out of the active area. On the one hand, the technologies closest to conventional two-side-contacted solar cells, widely referred to as metal wrap-through (MWT) and emitter wrap-through (EWT), rely on the same mechanism for extracting the generated carriers, namely cross-sectional conduction. In these cases the carriers collected at the front still need to be transferred to the contacts at

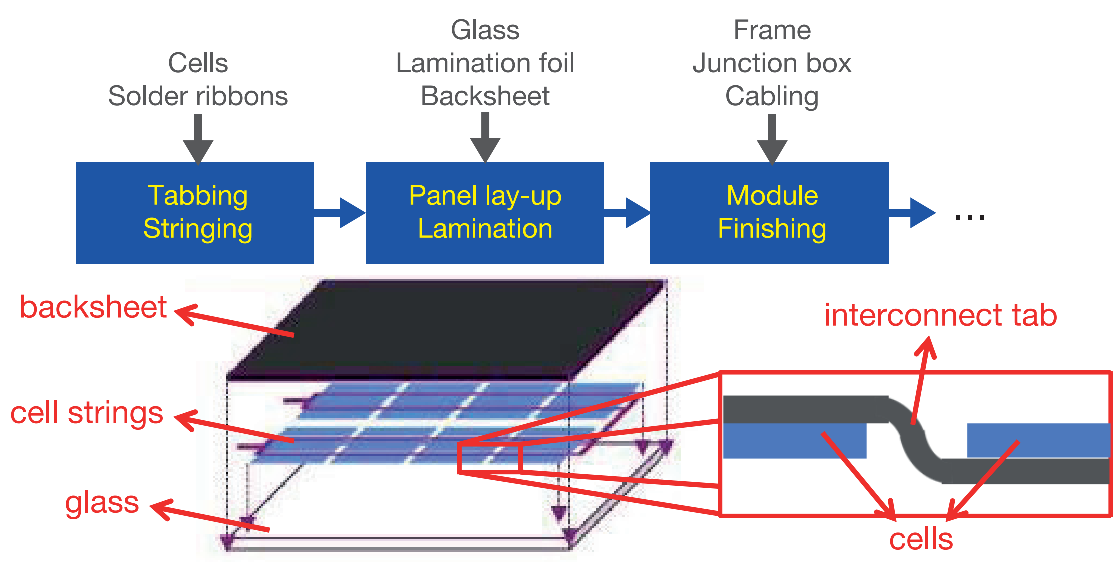

Figure 1. Typical flow diagram of conventional module fabrication.

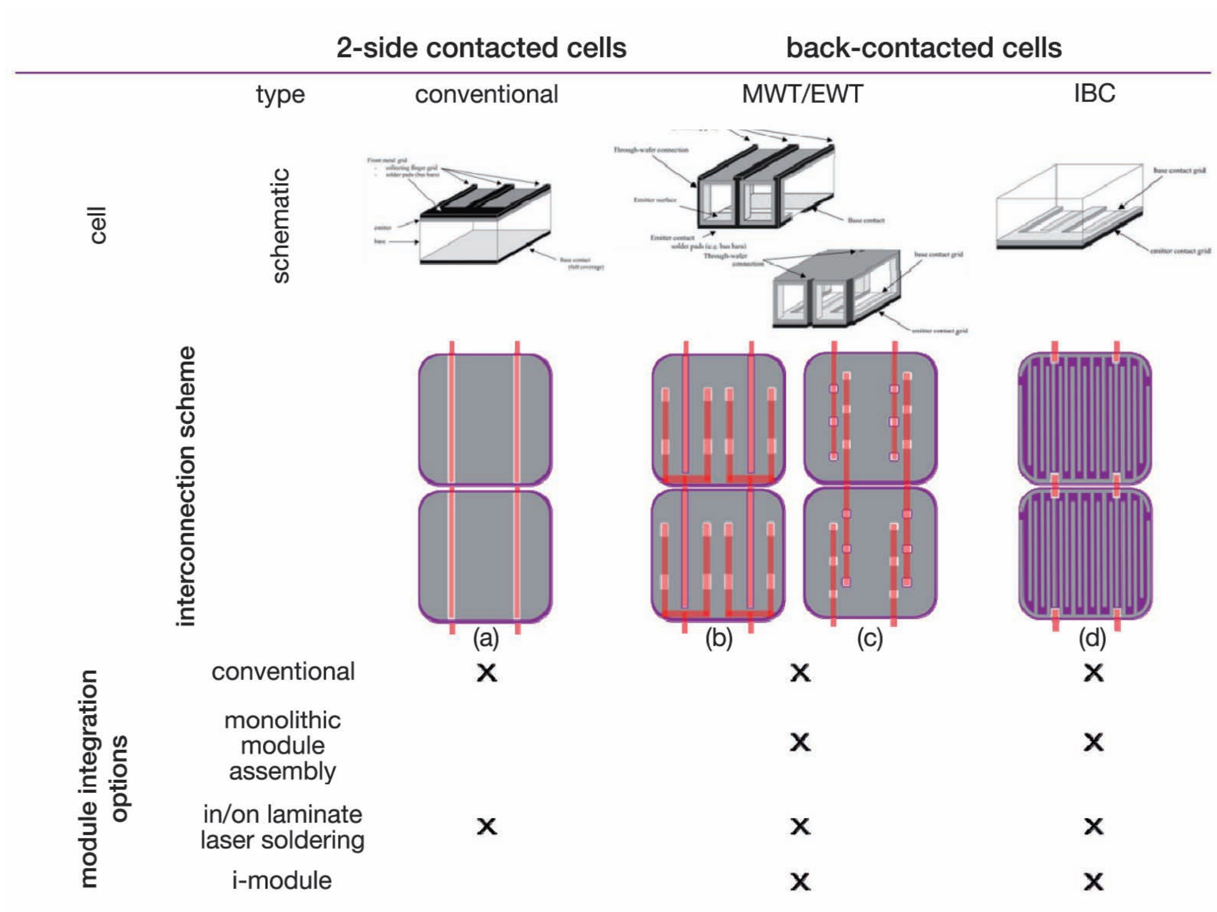

Figure 2. State-of-the-art back-contact cell concepts and module interconnection schemes (the red lines indicate the interconnect routing but its actual shape can be very different).

the back, which is done through vias in the silicon (hence 'wrap-through'). On the other hand, the interdigitated back-contact (IBC) cells do not extract carriers on the front, but instead both polarities are contacted at the back through an interdigitated grid. A schematic of the above cell concepts is shown in Fig. 2 (from Van Kerschaver and Beaucarne [2], where more details can also be found). For the interconnection of such finished cells, the routing schemes that are typically used are also indicated in the figure.

Interconnection can be achieved by tabs on the rear side only, or by using a conductive backsheet foil. Both have benefits compared to two-sided tabs. In the overview in Fig. 2, some important differences in module technology between conventional two-side-contacted and back-contacted cells are of interest. First, as there are no longer tabs at the front (so the topography and metal coverage is reduced), the encapsulation material for bonding the strings to the front sheet can be thinner (reduced material usage and reduced absorption losses). Second, the interconnections from one cell to the next are no longer kinked (from front to back) but are in-plane. This is advantageous since it means cells can be positioned closer to one another, but, at the same time, because the kink provides some stress relief during thermal cycling, the interconnect design should also take into account such stress-relief considerations. Third, by having all interconnections (using either tabs or a foil) at the rear there is more freedom of design: the interconnects can be designed (e.g. widened, tapered) to reduce series resistance and hence fill factor (*FF*) losses, and optimally distribute the current running through the interconnects. In this way, the interconnection scheme can be electrically optimized for module output, material usage and cost. Indeed, using MWT cells and an interconnection foil has resulted in a world record for multicrystalline modules [3,4].

In a design such as in Fig. 2(b), one set of busbars can be kept, and it is in this sense closer to conventional technology; however, rerouting of the interconnects from one cell to the next is required for this scheme. In a design such as in Fig. 2(c) or (d), a straight-line interconnection may be kept (although for the layout given in Fig. 2(c), the cells have to be rotated 180 degrees relative to the preceding and following cells). In addition, for the layouts of Fig. 2, in order to avoid shunting the cell an insulation layer is required wherever the interconnect crosses the metallization with opposite polarity on the back side of the cell. This extra insulation layer can be avoided in the layout of Fig. 2(d), as the interconnects do not need to cross the other polarity of the cell, owing to the interdigitated structure of the cell metallization.

Adaptation of conventional technology to back-contact solar cells [5,6,7,8,9]

The back-contact cell and module technology most closely related to conventional technology (based on two-side-contacted cells) is based on soldering the back-contact cells into strings, followed by lamination between the front glass and the backsheet using EVA.

> "Module-to-cell power ratios of over 98% have been obtained."

Photovoltech has developed such a stringing technology for its MWT cells. The main design goals of the approach were to avoid product reliability concerns by using materials that were as close as possible to those of existing module

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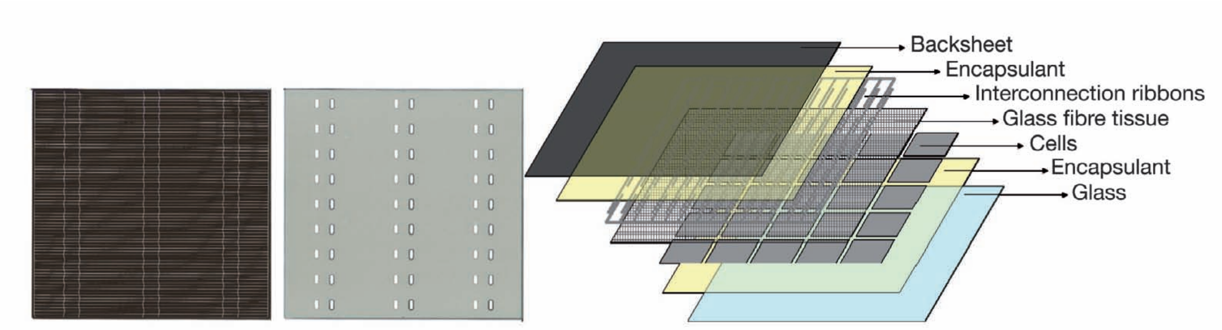

Figure 3. Front and back pattern of a Photovoltech MWT cell and the make-up of a module.

technology, and keeping the costs low by using commodity materials. The interconnection is based on the geometry described in Fig. 2(c) and thus requires an insulation layer between the cells and the ribbon conductors. The insulating layer is an open-structured glass fabric that does not require any alignment to the cells. To bridge the fabric between the ribbons and the cells, solder paste is applied. Module-to-cell power ratios of over 98% have been obtained. The width of the ribbons can be chosen to optimize the resistive losses in relation to the copper market price. The tabber-stringer equipment had to be modified to handle the fabric and paste dispensing. Details of the implementation of this approach and the tests carried out will be published in due course.

SunPower, widely acknowledged for its high-performance cells and modules, produces high-efficiency back-contact cells based on 'low-cost' alternatives for a lithography-based process flow on wafers with a high minority-carrier lifetime. As illustrated in Fig. 4, the cell relies on an IBC structure, and modules are fabricated using specifically designed straight-line interconnected strings (as in Fig. 2(d)), laminated between the front glass and the backsheet using EVA.

Monolithic module assembly [10,11,12,13,14,15]

The technology based on conductive backsheet foils has been developed by ECN and allows for an integrated cell and module approach. The conductive backsheet consists of PVF-PET-Cu foil, and the Cu foil is patterned according to the required interconnection scheme. Electrical contact between the cells and the foil is made by printing a conductive adhesive on the foil. The cells can be placed on the foil with adhesive by a gentle pick-and-place process. The adhesive is cured simultaneously in the lamination process of the encapsulant and thus does not require any additional processing, which means that this process is also suitable for thin wafers. Because of the simplified interconnection procedure, the monolithic module assembly process is up to six times as fast as conventional module manufacturing requiring tabber-stringer and lay-up stages. The manufacturing process of this type of MWT module has been developed in collaboration with the Dutch company Eurotron, and fully automated production lines with a capacity of up to 150MWp per line are now operational. MWT modules using this concept have obtained IEC 61215 and IEC 61730 certification [11]. A similar module fabrication technology is also under development at Applied Materials, but for EWT cells.

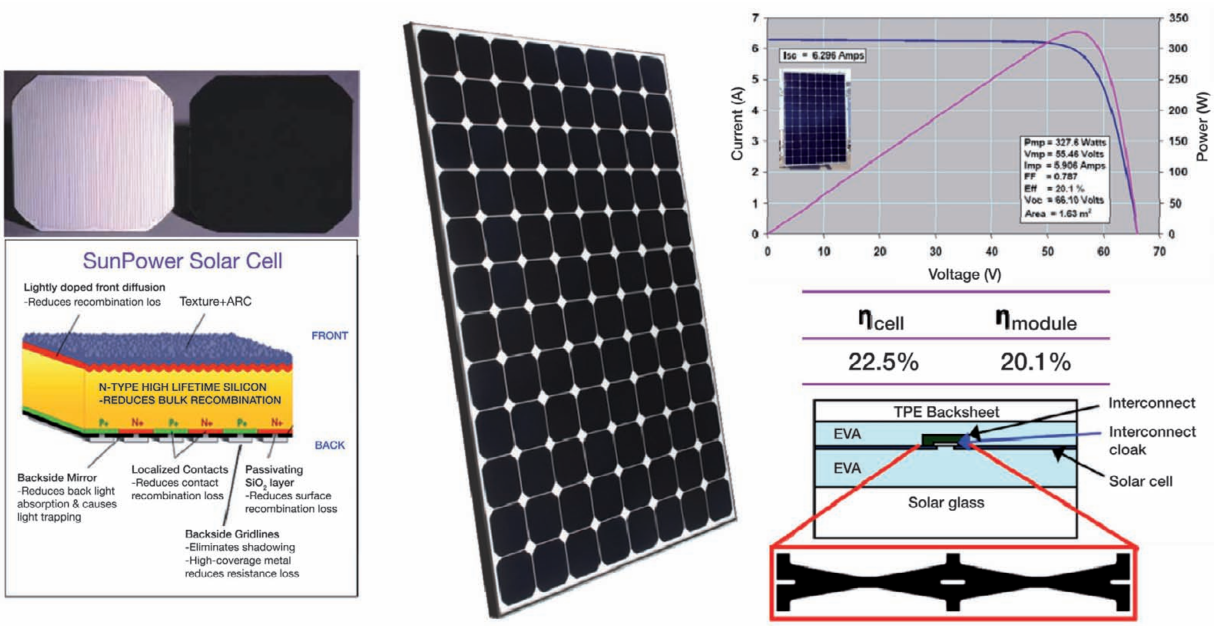

Figure 4. Make-up and performance of a SunPower (IBC) cell and module.

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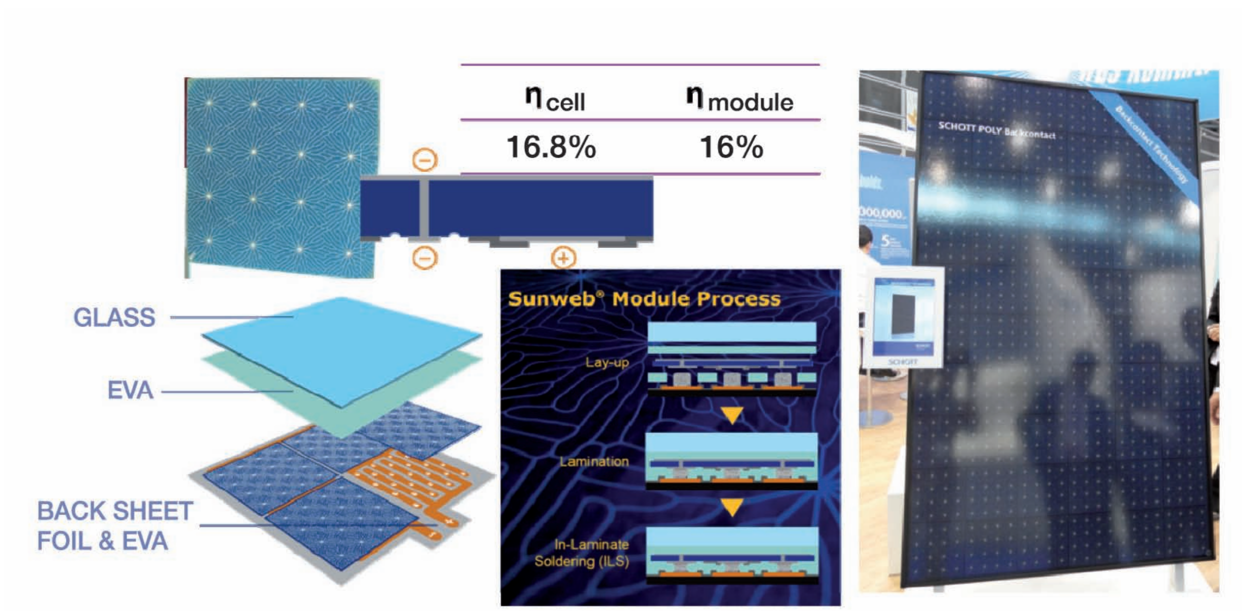


Figure 5. Make-up and performance of a Sunweb (MWT) cell and module.

"The monolithic module assembly process is up to six times as fast as conventional module manufacturing requiring tabber-stringer and lay-up stages."

In-laminate laser soldering [16,17,18,19,20]

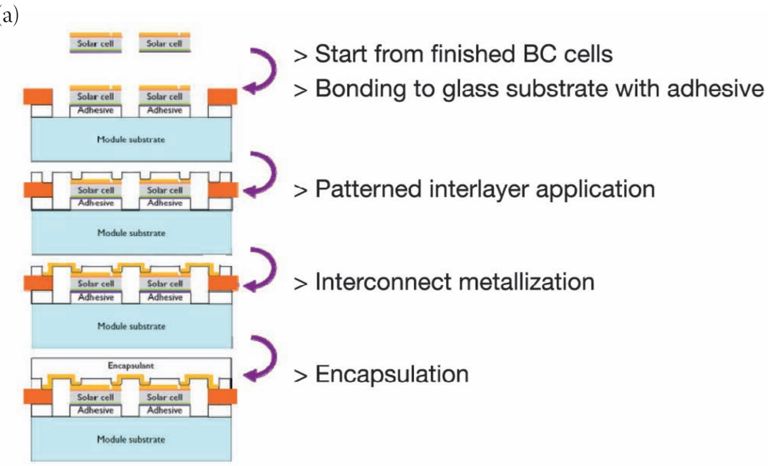
At a time when the long-term reliability of conductive adhesives had not yet been proved in the field, a similar concept was proposed and developed on the basis of the industrially accepted soldering benchmark. In this case the construction closely resembles the above monolithic module assembly approach, but instead of conductive adhesive, a solder paste is dispensed on the patterned conductor backsheet. The cells are then placed and laminated as before on a front glass superstrate.

Since the lamination is typically carried out at around 150°C for EVA, and standard soldering requires temperatures of around 230°C, the interconnect tabs are not yet properly soldered during lamination. Therefore, after lamination, the tabs are soldered by laser to the backsheet contacts through the front glass. Alternatively, the tabs could be soldered prior to the lamination stage, but the laminated stack ensures a better defined contact pressure during laser soldering, which improves the reproducibility of the resulting joint. The concept is illustrated in Fig. 5. A potential simplification of this scheme, by making use of Al–Al direct laser welding, is currently also under development [21].

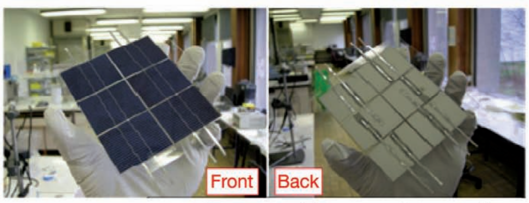
i-module [22,23,24]

As mentioned earlier, the conventional module fabrication approach requires the soldering of standalone cells and

(a)



(b)



	Jsc (mA/cm²)	Voc (mV)	FF (%)	Eta (%)
cell 4	35.8	607	76.8	16.7
cell 5	35.8	609	76.3	16.6
cell 6	36.2	603	76.5	16.7
series 456	35.7	1823	76.9	16.7

Figure 6. (a) Schematic overview of the i-module concept; (b) an i-module based on MWT cells interconnected by soldering.

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		Conventional adapted for back-contact cells	Monolithic Module Assembly	In-laminate Laser soldering (ILS)	i-module
Technology	Encapsulation method	Full-stack lamination	Full-stack lamination	Full-stack lamination	Sequential layer buildup
	Encapsulation material	EVA sheets	Sheet-based encapsulants (EVA, thermoplastic, silicone)	Sheet-based encapsulants (EVA, thermoplastic, silicone)	Gel-based encapsulants
	Interconnection method	Soldering, conductive adhesives	Conductive foil and adhesives	Laser soldering	Soldering, thin-film metallization, printing
	Interconnection level	Cells/string-level before lamination	Module-level during lamination	Module-level after lamination	Module-level (intermediate)
Performance	Module-to-cell power ratio [%]	Photovoltech (MWT) 98 SunPower (IBC) 103	ECN (MWT) 97 Kyocera (MWT) 96 Photovoltech (MWT) 96	Solland (MWT) 102	Imec (MWT) 104 (small area)
	Reliability	lifetime guarantee 25 years	IEC certified	lifetime guarantee 25 years	Tbd
	Level of maturity	in mass production	industrial pilot-line production	industrial pilot-line production	R&D phase

Figure 7. Overview of the differences in technology and performance for the different back-contact module concepts (ratio values obtained by calculations based on public information).

the handling of long strings of cells prior to lamination, two steps in which (micro) cracks may easily be introduced, especially in the case of very thin cells (e.g. thicknesses of 100µm and below). The i-module (interconnect-module) approach aims to minimize the risk of cracks by providing a module-level interconnection that is created only after attaching the cells to the module substrate (glass). This is of course only possible if all of the cells' contacts are still available at this stage, and thus the approach requires back-contact cells.

An adhesive layer (typically silicone such as reported in Ketola et al. [25]) is applied to a clean glass module superstrate, and the solar cells are placed with the front ('sunny') side towards the glass, so that the contacts remain available for processing on the rear side. To isolate the emitter and base contacts, a dielectric layer is subsequently deposited, with holes so that the cells' contacts remain available. A metallization is applied to interconnect (e.g. serially) the different cells in the module; outside contacts are then provided and the stack is encapsulated to protect the metallization and reinforce the assembly. The process flow diagram is shown in Fig. 6(a).

For each of the different steps, several technology options can be (and already have been) considered, as reported in Govaerts et al. [22–24]. Attention is focused on a demonstration module that is the one closest to being industrially adopted in the short term. This proof of concept is based on MWT cells (provided by Photovoltech) with a typical thickness of 180µm. The dielectric layer on the back side of these cells has been selectively deposited (screen printing and dispensing – both are feasible) to isolate the front interconnects from the back side, and soldering has been chosen as the method of interconnection. Fig. 6(b) shows the results for such a demonstration module.

Summary and outlook

In overview, the different module fabrication concepts could be classified, for example, according to the moment when the cell interconnection is established. At one end of the spectrum lies conventional module technology, where cells are soldered (standalone) prior to lamination. At the other end, there is the in-laminate laser-soldering concept, which only finishes the interconnection after the full stack has been laminated. In between these two, monolithic module assembly provides interconnection during lamination. The i-module approach splits the full stack lamination, providing an intermediate level, closer to the sequential build-up of layers common in the fabrication of printed circuit boards. Fig. 7 highlights the classification of the concepts, along with the characteristics of each one.

The viability of several of the above basic concepts has been proved; some are in production, or close to production, and many hybrids of these can still be conceived. However, the existence of many different layouts for the contacts of back-contact cells (justified or not) implies that no standard interconnect routing scheme has so far been widely accepted in the industry. This is a drawback in the sense that it does not allow a straightforward comparison to be made between the different cell technologies with the same module technology, or between the different module technologies with the same cells.

In a broader perspective, however, if cell and module technology cannot be decoupled, this interdependency implies that companies in this area will have to vertically integrate to ensure the quality of their products. In this way, the back-contact c-Si module technology is likely to converge more and more on thin-film organic or inorganic technology. Both c-Si and thin-film technologies are increasingly targeted towards module-level performance (and processing), with the former evolving towards lower cost, and the latter evolving towards higher efficiencies and reliability.

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Jonathan Govaerts received his Ph.D. degree 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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Jef Poortmans received his degree in electronic engineering from the Katholieke Universiteit of Leuven, Belgium, in 1985, and his Ph.D. degree in June 1993. He is the director of the Solar and Organic Technologies Department at imec, and is currently director of the SOLAR+ strategic programme, which comprises all the photovoltaic technology development activities within imec. Jef has also been a part-time professor at the Katholieke Universiteit since 2008.

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Wouter Ruythooren received a Ph.D. in 2002 from the Katholieke Universiteit Leuven, Belgium, for his study on the electro-deposition of magnetic materials for integrated components. He then developed GaN device processing technology at imec until 2005, after which he became manager of the R&D teams, focusing on 3D packaging and electrochemical deposition. Wouter has led the back-contact technology group at Photovoltech since 2010.

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