tandemPV: A review of c-Si-based tandem technology and what is needed to bring it into production

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Abstract

In the last decade the field of PV has become extremely dynamic in terms of implementation of innovations within solar cell development and module production. Al-BSF devices are beginning to fade out as more-advanced and higher-efficiency solar cells and modules enter the PV market. It is believed that c-Si-based tandem solar cells will also be commercially available within three to five years (possibly sooner), as also confirmed in the ITRPV roadmap. This paper provides a concise overview of existing c-Si-based 2-, 3- and 4-terminal tandem technologies, summarizes the current development status, and sets out the future roadmap. In addition, a discussion is included of what will be required over the coming years to bring these promising technologies to market, enabling commercial efficiencies above 30%.

Introduction

It has become universally accepted that PV will be one of the main technologies to mitigate global warming. Considering that PV has only become cost effective in the last two years – meaning that it is now possible to install PV systems reaching values of levelized cost of energy (LCOE) of US$30/MWh and below without subsidies – we are only at the beginning of this success story. The total worldwide installed power of PV systems up until Q2 2020 was about 650GWp, and it is expected that this figure will reach 1TWp by the end of 2022 [1]. The current module price is around US$0.2/Wp, and there is the potential to reduce this to US$0.1/Wp in the coming years [1]. By 2050 about 30–50TWp of installed PV power is anticipated, which will be about 30–50% of total electricity generation [1]. Which PV technology has been responsible for this magic? It was, and currently still is, crystalline silicon (c-Si)-based PV technology.

In 2009/10 Martin Green proposed that c-Si technology (G1: Generation 1) was a good start for PV but that in the future, Generation 2 (i.e. thin film) and later Generation 3 (i.e. tandem applications) will be needed in order to achieve 'low-cost module regions' below US$0.5/Wp (Fig. 1). Already by 2013 it had become apparent that c-Si technology was more powerful than expected because of rapid technology improvements coupled with the move to mass production in China. Moreover, instead of pursuing further development in different generations, the PV market adopted thousands of small evolutionary innovations in production, reaching lower and lower production cost. Now, in 2020, we are in the middle of the proposed 'G3 area', and it is clear that c-Si will

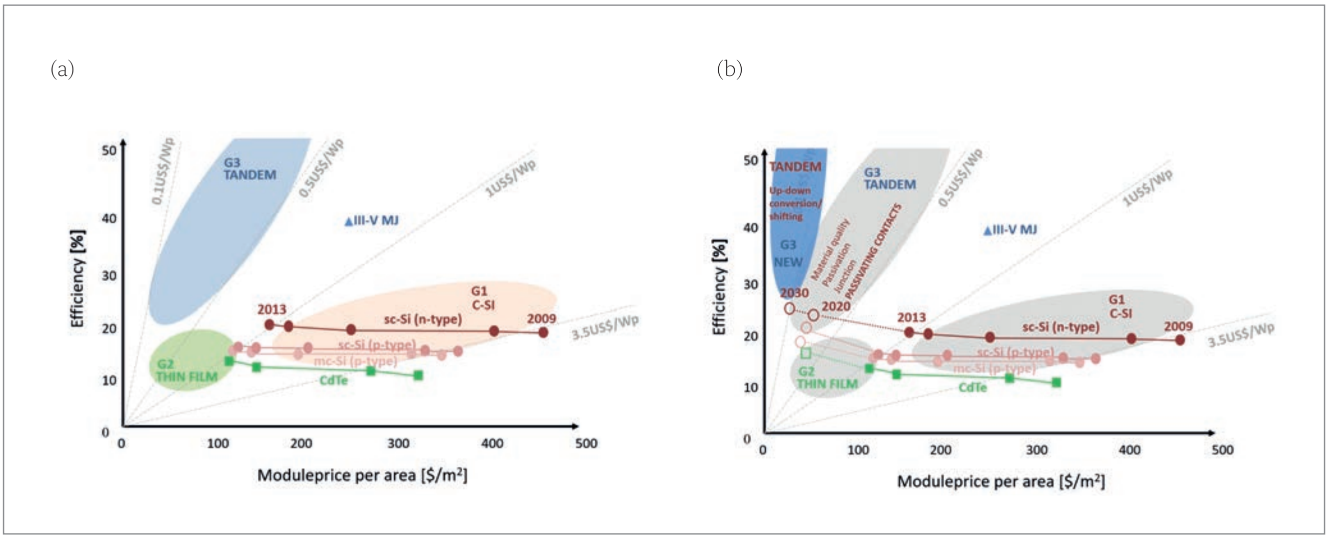

Figure 1. (a) Forecast from Martin Green [2] for different PV technologies. (b) Reality in 2020 and forecast for 2030.

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continue to be the leading technology in the near future. Over the next 10 years it is expected that c-Si technology will be driven to its efficiency and cost limits, with modules reaching a low cost of the order of US$0.1/Wp.

At the moment, the lowest cost technology is the so-called standard *passivated emitter and rear contact (PERC)*, but this technology is getting close to its practical efficiency limit of around 23% (with a V_{oc} of about 685mV). Final efforts are being made to break through the 23% ceiling with the inclusion of selective emitters and by using Ga-doped c-Si wafers as standard. The drive to reduce costs further, however, is now being tackled mostly by increasing the substrate sizes from M2–M6 up to M10 and perhaps M12 in the future. Higher module efficiencies for PERC technologies are being achieved with more advanced layouts and interconnection concepts, such as shingling or zero-space connections. In 2020 more n-type concepts have been gaining importance, since efficiencies well above 23% are possible using passivating contacts, including silicon heterojunction (SHJ) technology, but the practical limit of 27% of such concepts is also getting closer. On a fundamental level, the only practical ways to exceed the Shockley-Queisser thermodynamic limit of single-junction photovoltaics is either through the use of up/down conversion layers, or by combining multiple solar cell junctions into so-called *tandem configurations*, which have the potential to achieve commercial efficiencies above 30% in the near term [3].

In this context, many consortia in the EU now believe that the next big step in PV is not an evolution but a small *revolution* – heading towards c-Si-based tandems using standard technology as the low-band-gap bottom cell, different absorbers for the high-band-gap top cell, and different interconnection schemes for the top and bottom cells. Fig. 2 shows the International Technology Road Map for PV (ITRPV) forecast for future c-Si-based technologies.

In the ITRPV roadmap, the fading out of Al-BSF technology can be clearly seen as it is replaced first by standard PERC, and then later by more advanced technologies, such as 'TOPCon' (e.g. the latest record of Jinko of 24.8% [4]), which can produce voltages of over 700mV, and silicon heterojunction reaching 25% efficiency [5]. From 2024/25 onwards, it is anticipated that c-Si-based tandem technologies will begin to appear, but precisely which tandem technologies, and what will be required for this to really happen, will be discussed in the following paragraphs. In order to further support these promising technologies to come onto the market, the first c-Si-based tandem workshop – tandemPV – is also being organized from 2020 onwards (see www.tandemPV-workshop.com).

Apart from economic and market factors, c-Si also exhibits a range of other characteristics that make it suitable as the bottom cell in a tandem architecture; for example, it is abundantly available, inexpensive and efficient, and has a near-ideal band gap for achieving the maximum power conversion efficiency of a tandem solar cell. Last, but not least, there have been impressive industrial developments and achievements in relation to single-junction photovoltaics that are fundamental to the deployment of tandem technology as well. If c-Si solar cells are used just for the bottom cells, many costs can be reduced significantly, with potential savings in, for example, metal paste consumption.

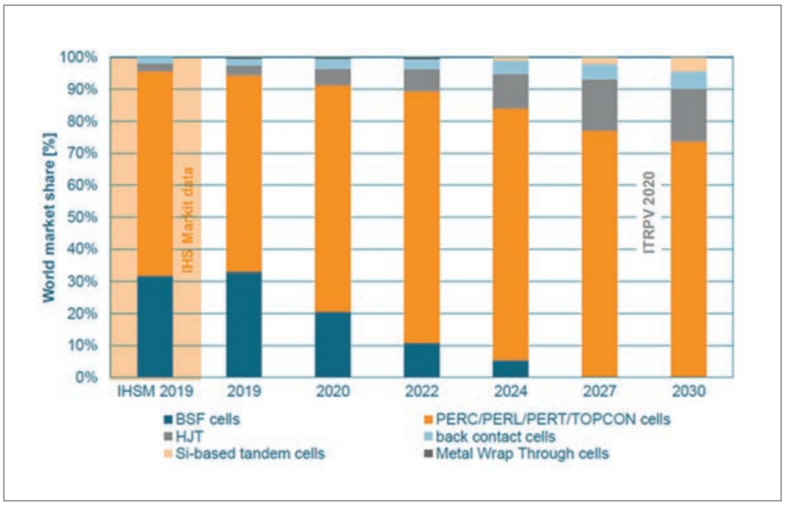

Figure 2. ITRPV roadmap for future c-Si-based solar cell technologies [1].

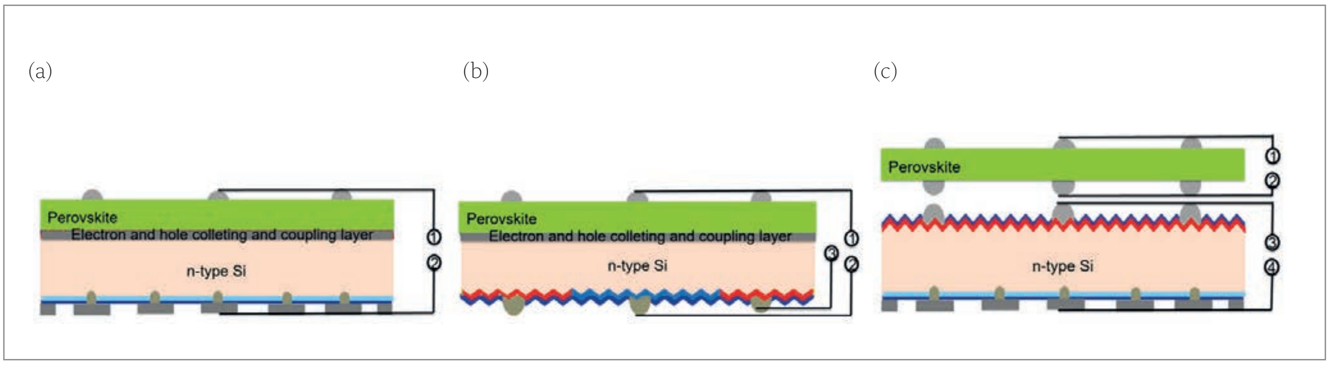

Figure 3. Schematic cross sections of different tandem geometries: (a) 2-terminal (2T); (b) 3-terminal (3T); (c) 4-terminal (4T).

Tandem terminal geometries

For c-Si-based tandem technologies there are several basic geometries that can be used, namely 2-teminal (2T), 3-terminal (3T) and 4-terminal (4T) tandem approaches, as depicted in Fig. 3.

The selection of the c-Si devices best suited to the corresponding technologies is fairly straightforward and depends on the targeted application. However, this concept brings with it the challenge of identifying an efficient top cell.

Suitable technologies for top cells

As candidates for a thin-film top cell absorber there are many possibilities, including perovskites, GaAs and other III-V devices, CdTe and CIGS, of which some are better and some worse in many respects. The most promising options these days for top cells are metal-halide perovskites and GaAs, with both having their respective advantages and disadvantages. For example, perovskites can be made at low cost but improving the stability is still a major focus of R&D efforts; in contrast, GaAs layers are highly stable but the deposition techniques are still not sufficiently cost effective. There are many groups, however, that are tackling these challenges. In the following paragraphs, the status of the most promising candidate – the perovskite top cell – will be briefly summarized.

Perovskite photovoltaics have been proved to enable silicon to go beyond its single-junction limit. Since their solar absorber properties were first discovered in 2009, perovskites have become one of the most prominent research topics in the PV research community. With exceptionally rapid improvements in efficiency, stability and scalability over the last five years, the potential of perovskite photovoltaics has been grasped and they are now entering their commercial phase. Certified efficiencies are now as high as 25.5% for perovskite single junctions, and 29.15% for 2T perovskite–silicon (PVSK–Si) tandem cells [6]. Advances in efficiency have been supported more and more by progress in device stability under accelerated ageing tests [7]. A range of deposition techniques exists – from solvent-based to entirely solvent-free coating techniques, and any combination in between – that can be employed to fabricate a perovskite solar cell on top of a silicon bottom cell to form a PVSK-Si tandem solar cell. Perovskites are therefore well suited to conformal deposition on a variety of surface textures [8] and over large areas [9], which is necessary for successful tandem fabrication on a commercial scale.

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For PVSK-Si tandems, it is crucial that the overall module stability approaches the level of stability of silicon-only modules, otherwise the benefits of the higher initial efficiency of tandem modules is reduced or eliminated. To ensure this, the continued focus of the PV community on advancing the stability of these cells, and on their evaluation by accelerated ageing tests already in use in the silicon industry, is essential (e.g. IEC 61215). Ultimately, however, extended outdoor testing must be undertaken to verify such testing. Fig. 4 shows the normalized weekly output of two monofacial modules installed at Oxford PV GmbH's manufacturing site in Germany. One module is an industrial 60-cell PERC module and the other, a 60-cell 2T PVSK-Si module. Thus far in the six months of data collected, there is no visible divergence between the performance of the two module types. If anything, the tandem module has increased in performance relative to the PERC module during the year, probably because of the superior high-temperature performance of the tandem module. Clearly, the work of fully validating the reliability and bankability of any new technology takes time, but for 2T PVSK-Si tandems, the signs are good.

Suitable c-Si technologies for bottom cells

In addition to the quest for a suitable top cell material for the Si-based tandem, the type of c-Si bottom cell and the scheme used to interconnect the

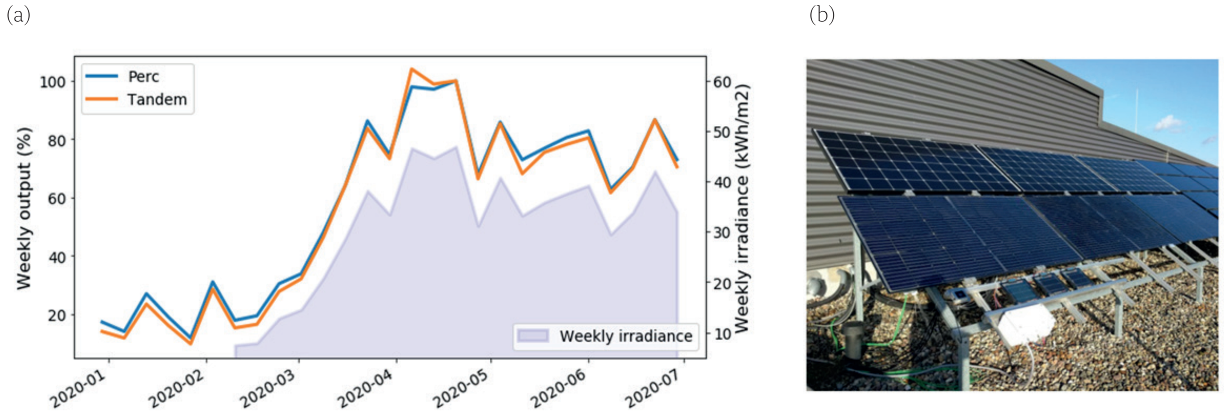

Figure 4. (a) Normalized weekly output of standard PERC vs. 2T PVSK-Si modules at Oxford PV GmbH's manufacturing site in Germany. (b) The outdoor testing site.

top and bottom cells are important aspects requiring careful consideration. All interconnection schemes come with their pros and cons, and for c-Si-based tandems these can be summarized as follows.

In a *2T tandem*, the different absorbers are connected in series. This facilitates an easy and straightforward implementation of the tandem solar cells into modules similar to a standard two-side-contacted c-Si module. In *2T and 3T tandems* the top and bottom cells are monolithic in nature. On the one hand, this is beneficial in terms of saving any additional fabrication costs (e.g. glass substrate for the top cells). On the other hand, this quite likely requires process adaptations of a high-temperature c-Si PERC process to incorporate the low-temperature-processed top cell. Additionally, in order to avoid major power losses in *2T tandems*, the series-interconnected top and bottom cells must have their currents closely matched at their maximum power points and this requires thorough band-gap engineering of the top cell's absorber. However, in *3T and 4T tandems*, the top and bottom cells do not need to be current matched, and therefore provide a more flexible choice in band gap for top and bottom cells.

From an industrialization point of view, it is beneficial for any bottom cell technology to be as close as possible to the dominant PERC technology in order for existing production capacities to be upgraded. From a technical point of view, the best-suited bottom solar cells for the 2T approach are two-side-contacted cells with passivating contacts, e.g. SHJ or poly-Si solar cells [10–11], with open-circuit voltages exceeding 720mV. One possible PERC-like bottom cell with a passivating poly-Si front contact with an integrated tunnelling junction was proposed by Peibst et al. [12].

In a *4T tandem*, the two absorbers are physically connected but their electrical operations are independent. This necessitates a relatively complex module implementation – basically having two separate modules on top of each other, which could make this configuration quite costly. On the other hand, this provides the greatest flexibility for achieving the highest efficiency as well as an easy implementation of bifaciality, and without any of the current mismatch losses of the two-terminal configuration. Here, an ideal bottom cell could be the very low-cost but high-efficiency rear emitter passivated emitter rear totally diffused (nPERT) solar cell, since the rear emitter is best suited to red/IR absorption, as well as offering the best use of bifaciality. However, a PERC cell with a poly-Si emitter also has the potential to be a suitable bottom cell for both 2T and 4T tandems [13], with good near-infrared (NIR) response, in particular when Ga doped for good bulk lifetime; moreover, PERC cells can be produced for bifacial operation.

Recently, the *3T tandem* configuration has attracted increasing interest, as it combines the positive aspects of both 2T and 4T tandems. Thus, with a potentially higher energy yield, due to better optics from the monolithic structure and without the intermediate grid of the 4T, the 3T tandem could provide a path towards lower LCOEs. Here, the natural choice is an interdigitated back-contact (IBC) solar cell, since the rear-contact design allows the use of just an interconnection layer(s) between the top and bottom cells.

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2T tandem technology

Oxford PV is pursuing the commercialization of perovskite technology in a 2T approach for the following reasons:

1. It provides the silicon industry with a viable route to achieving efficiencies beyond 25%.

2. Integration at the cell level minimizes optical and resistive losses.

3. It yields a final module product with higher power, which can be indistinguishable from a standard silicon module in terms of installation and integration.

4. Finally, and most importantly, a cost of ownership analysis has shown that silicon solar cells enhanced with Oxford PV's perovskite solar cell technology will lower the LCOE of a solar installation – a critical consideration for delivering more affordable clean energy and accelerating the adoption of solar energy, thus mitigating the impact of climate change.

Moving from record-efficiency lab-scale devices to a commercially viable product requires the ability to produce perovskite cells on a full-wafer scale. This can be achieved by an appropriate choice of deposition processes. Additional processes are also required – ones that are not used on a small scale. One of the key drivers of efficiency for conventional silicon solar cells has been improvements in metallization technologies – 2T tandem cells similarly require low shading and low resistivity interconnects, with the additional requirement of low process temperature.

Fig. 5 shows that from a subset of the wide variety of pastes available for SHJ cell metallization there are very different responses of resistivity to temperature. Paste D, for example, shows very little difference in resistivity, whether baked at 60°C or 150°C, whereas paste C changes by two orders of magnitude over the same range. As well as the resistivity, which must be low to maximize fill factor, the shading must be kept low to maximize current output.

As a demonstration of the scalability, a 4cm^2 cell was created with screen-printed front electrodes; the device parameters are shown in Table 1, compared with a previously certified 1cm^2 cell, which does not require a front grid. As can be seen, in contrast to the record cell, there is no change in fill factor, signifying that the electrical properties of the metallization are sufficiently good. There is a slight loss in J_{sc}, which is accounted for by the 2.5% shading resulting from the silver fingers. Overall, this yields a high-efficiency cell fabricated using standard industrial metallization techniques.

As is well understood, bifacial cells and modules consistently offer an advantage over their monofacial counterparts. It is often mistakenly thought that, because of their requirements for current matching, 2T tandem cells are incompatible with such energy-yield-enhancing approaches. By using an equivalent circuit model to elucidate the change in response of the device to different photocurrent generation in the two subcells, it is possible to quantify the effects of this divergence from matching, as well as the gains from rear illumination. Since the requirement for current matching exists in these tandem cells, any gain in current from rear illumination is constrained by the top cell current. The model reveals (Fig. 6) that there is always a gain in fill factor as current mismatch increases (as previously reported in Koehnen et al. [14]), which leads to a gain in performance; to maximize the boost in output, it is preferred to adjust the band gap of the PVSK to capture more of the front illumination so that an increase in rear illumination increases the current in the device. Adjusting the band gap of PVSK materials is possible over a very wide range, as shown in Fig. 6, which draws on data from Oxford PV and data from Bush et al. [15]; such tandem cells can therefore take advantage of a bifacial design.

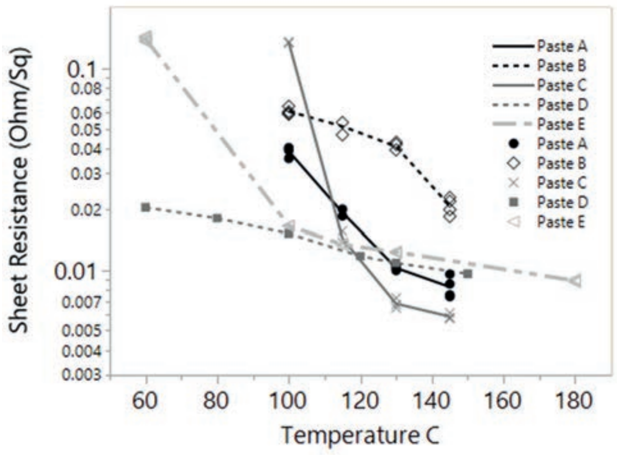

Figure 5. Measured sheet resistance for various metallization pastes.

Cell type	V_{oc} [mV]	J_{sc} [mA/cm^2]	*FF* [%]	η [%]
1cm^2 2T tandem	1.801	19.8	78.7	28.0
4cm^2 2T tandem	1.818	19.4	78.8	27.8

Table 1. *I–V* parameters for PVSK-Si tandem cells of different areas.

In summary, the 2T terminal approach is compatible with highly efficient, reliable modules, is able to use standard industrial metallization and interconnection approaches, and can demonstrate high energy yield, with the ability to benefit from bifaciality in much the same way as standard silicon modules.

3T tandem technology

There are many possible ways to construct a tandem solar cell with three terminals from a particular 2T top cell and a 3T interdigitated back-contact bottom cell (3T-IBC). The 3T-IBC cell is the heart of the 3T tandem cell, as it enables the 3T operation, and it is essential to understand the physics and operation principles of the 3T-IBC cell in order to understand the whole tandem cell's operation. Fig. 7 illustrates the operation principles of 3T tandem cells.

The 3T-IBC bottom cell in Fig. 7 has an n-type (silicon) absorber and three carrier-selective contacts. Two of the contacts – the front contact F

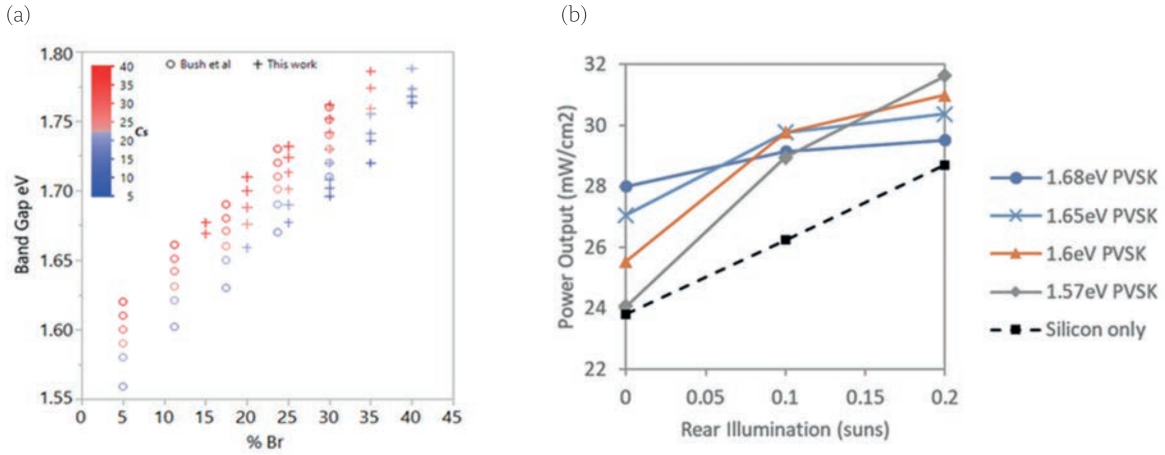

Figure 6. (a) Control of band gap in PVSK films, and (b) impact on bifacial performance [15].

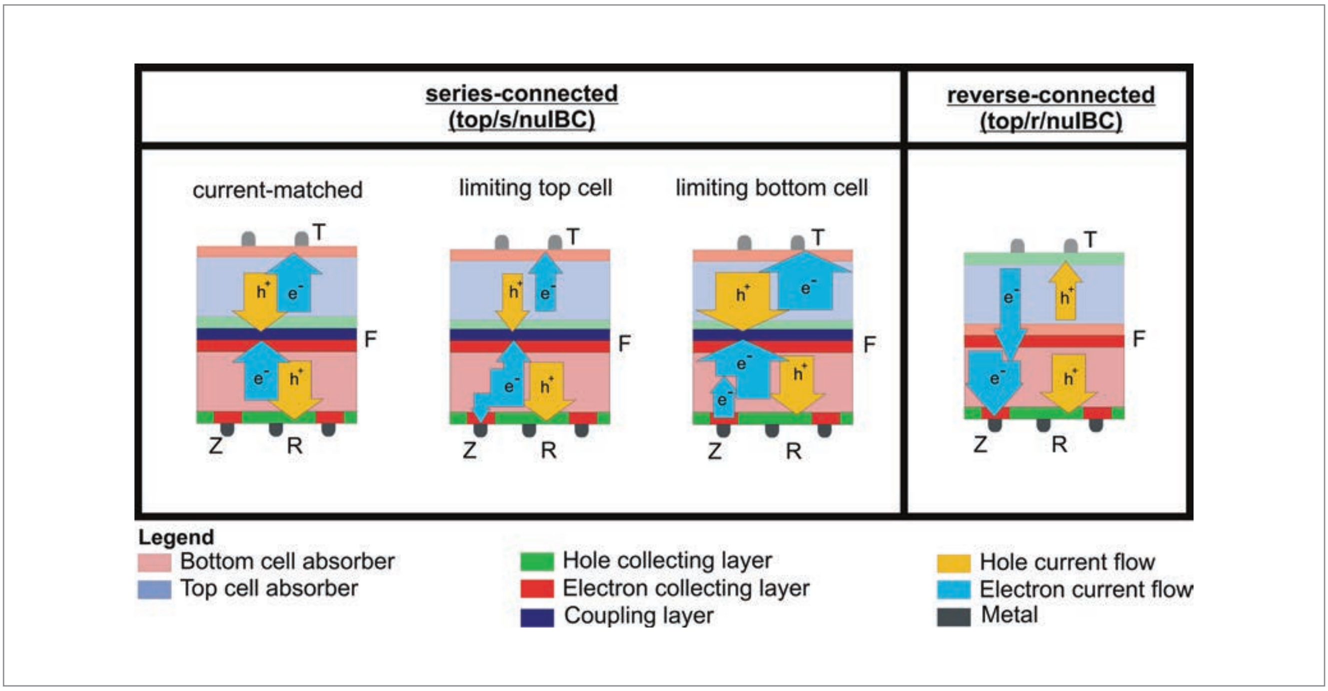

Figure 7. Different operation regimes of an n-type unijunction 3T-IBC bottom cell (nuIBC) in a series-connected tandem cell (top/s/nuIBC) with current-matched subcells, with current-limiting top cell and with current-limiting bottom cell, or in a reverse-connected tandem cell (top/r/nuIBC). The yellow arrows represent hole current flow and the blue arrows indicate electron current flow.

and rear contact Z of the bottom cell – are always of the same polarity, e.g. electron-selective in Fig. 7, and the remaining bottom cell's rear contact R has the opposite polarity, e.g. hole-selective in Fig. 7. If the absorber polarity matches that of the two contacts F and Z (as in Fig. 7), then the contacts F and Z are selective for the majority-charge carrier in the absorber. This 3T-IBC cell exhibits two majority-carrier contacts and a single minority-carrier contact, and is referred to as a *unijunction bottom cell* (according to the taxonomy in Warren et al. [16]). In contrast to the unijunction bottom cell, a 3T-IBC bottom cell with two minority-carrier-selective contacts F and Z and a single majority-carrier-contact R is denoted as a *bipolar junction bottom cell* because of its structural similarity with a bipolar junction transistor.

Despite the different architectures and physical descriptions of the unijunction and bipolar junction bottom cells, details of which can be found elsewhere [17–21], both types of bottom cell can be implemented in a 3T tandem solar cell in a similar way. Fig. 7 summarizes the different operation mode of 3T tandem cells comprising a unijunction bottom cell as an example, but which is also applicable to 3T tandems with a bipolar junction bottom cell [16–19].

In a 3T tandem solar cell, the top cell and bottom cell can be series connected as in a usual 2T tandem cell, where the selective contacts of the top and bottom cells with opposite polarity have to be interconnected by a coupling layer – typically a tunnelling or recombination junction. The series connection of the top and bottom cells implies that the current of the top cell's front contact T matches the current of the bottom cell's rear contact R. In a 2T tandem, meeting this current-matching constraint requires an adjustment of the photogeneration currents of the top and bottom cells. For the current-matched example in Fig. 7, this means that each photogenerated hole from the top cell finds a photogenerated electron from the bottom cell at the coupling layer, such that the whole photogenerated electron and hole current in the bottom cell is collected at the respective contacts F and R of the bottom cell. Since no surplus photogenerated electron current remains or is missing in the bottom cell, the additional contact Z is not required.

On the other hand, if the currents of the top and bottom cells are not matched (e.g. because of a varying illumination spectrum or because of mismatched band gaps), the current of a 2T tandem cell would be limited by the cell with the lower current, and the 2T tandem cell would underperform compared with a current-matched tandem cell. In a tandem cell with a limiting top cell (Fig. 7), the hole current of the top cell is less than the electron current from the bottom cell, such that surplus electrons remain in the bottom cell of a 2T tandem and recombine. In a 3T tandem cell, the additional contact Z enables the bottom cell to collect the surplus electrons and to generate extra power.

In a tandem cell with a limiting bottom cell, the photogenerated hole current from the top cell exceeds the electron current from the bottom cell, such that surplus holes remain and recombine in the top cell of a 2T tandem. However, the additional contact Z of a 3T tandem enables the bottom cell to balance the mismatched photogenerated currents of the top and bottom cells at the coupling layer by injecting surplus electrons into the bottom cell, allowing extra power to be extracted from

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the tandem cell. Ultimately, a series-connected 3T tandem cell provides a technology platform for maximizing the power output of a tandem cell with current-matched and current-mismatched subcells.

To demonstrate the proposed 3T concept, a collaboration of the National Renewable Energy Laboratory (NREL) in the USA and the Institute of Solar Energy Research Hamelin (ISFH) in Germany was able to fabricate the first series-connected 3T GaInP//Si tandem solar cell with an efficiency of 27.3% [22], and a series-connected 3T GaAs//Si tandem cell with 22.3% [23]. The former demonstrates the operation regime of a top-cell-limited tandem cell; the latter, that of a bottom-cell-limited one. Furthermore, Tayagaki et al. [24] have demonstrated a similar 3T GaAs//Si tandem cell.

Besides the series connection of the top and bottom cells, a 3T architecture provides another opportunity – the *reverse connection*, which is unique to the 3T tandem concept and was proposed by Nagashima et al. [25] more than two decades ago. To obtain the reverse-connected 3T tandem cell, the polarity of the top cell in Fig. 7 is flipped, and the top cell exhibits a hole-collecting front contact T and an electron-collecting rear contact. Since the top cell's electron-collecting rear contact meets the electron-collecting contact F of the bottom cell, this architecture does not require a tunnelling or recombination junction and might save the effort of implementing such a junction. Furthermore, it was proposed to use a single charge-carrier-selective layer between the two cells instead of a selective contact for each subcell [26]. The photogenerated electrons from the top cell are injected into the bottom cell, and the additional rear contact Z of the bottom cell collects the injected electrons from the top cell and the photogenerated electrons of the bottom cell. The corresponding holes are collected by the top cell's front contact T and the bottom cell's rear contact R. Even though this device architecture was proposed over two decades ago, Helmholtz Zentrum Berlin in Germany have only just recently managed to fabricate such a reverse-connected 3T perovskite/Si tandem cell, yielding an efficiency of 17.1% [27].

Interestingly, all experimentally demonstrated 3T devices in the literature have so far utilized 3T unijunction bottom cells, probably because of their intuitive operation principles. However, the 3T bipolar junction bottom cell is an attractive alternative, as recently pointed out by Rienäcker et al. [19]; it allows the construction of a lean fabrication process flow for a screen-printed and bifacial 3T-IBC bottom cell which is as simple as that for a PERC cell and reuses most of the fabrication tools for a PERC cell (Fig. 8).

Aside from the 3T cell architecture and technology, an important issue with 3T tandem technology is the integration of this type of cell into PV modules and systems. Interconnecting 3T cells is more complex than 2T or 4T cells, because of the wide variety of configurations and the lack of a simple repeatable unit cell. Gee [28,29], Borden [30], Schulte-Huxel [31,32] and McMahon [13] have shown that voltage-matching 3T devices can produce strings with two terminals and well-understood losses.

4T tandem technology

In a 4T tandem configuration the two absorbers are optically coupled and electrically isolated from each other. Because the two solar cells operate independently, there are consequential advantages but at the same time new challenges associated with the deployment of this configuration. The main advantage is that the two devices can be manufactured separately and therefore make use of the best specialized expertise and best specialized cost structure available on the market. In other words, the module manufacturer is free to select a

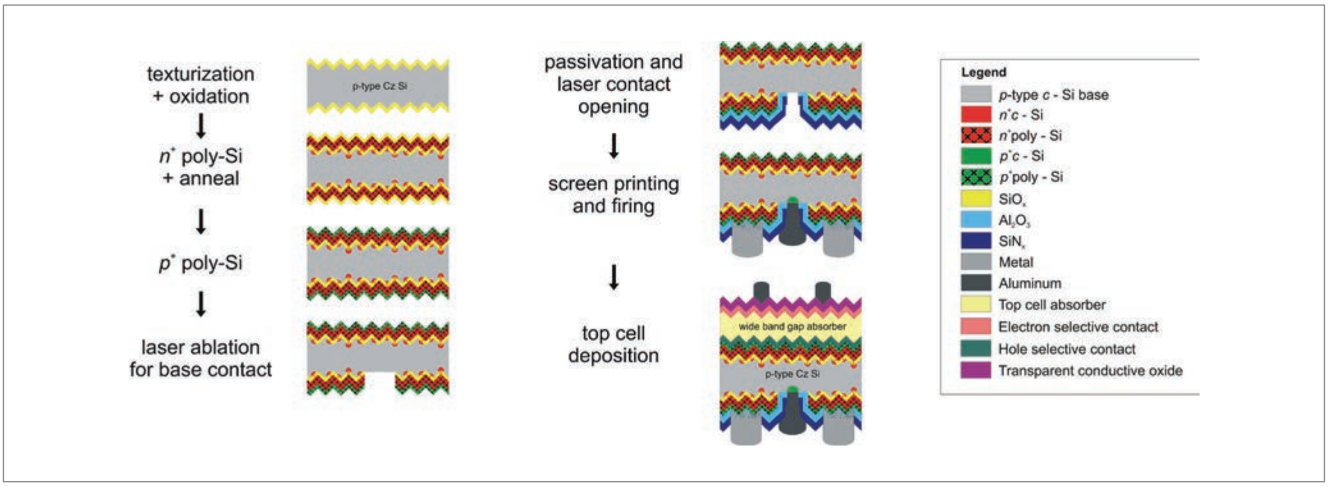

Figure 8. Proposed fabrication process for a 3T tandem cell comprising a PERC-like 3T bipolar junction bottom cell [19,21].

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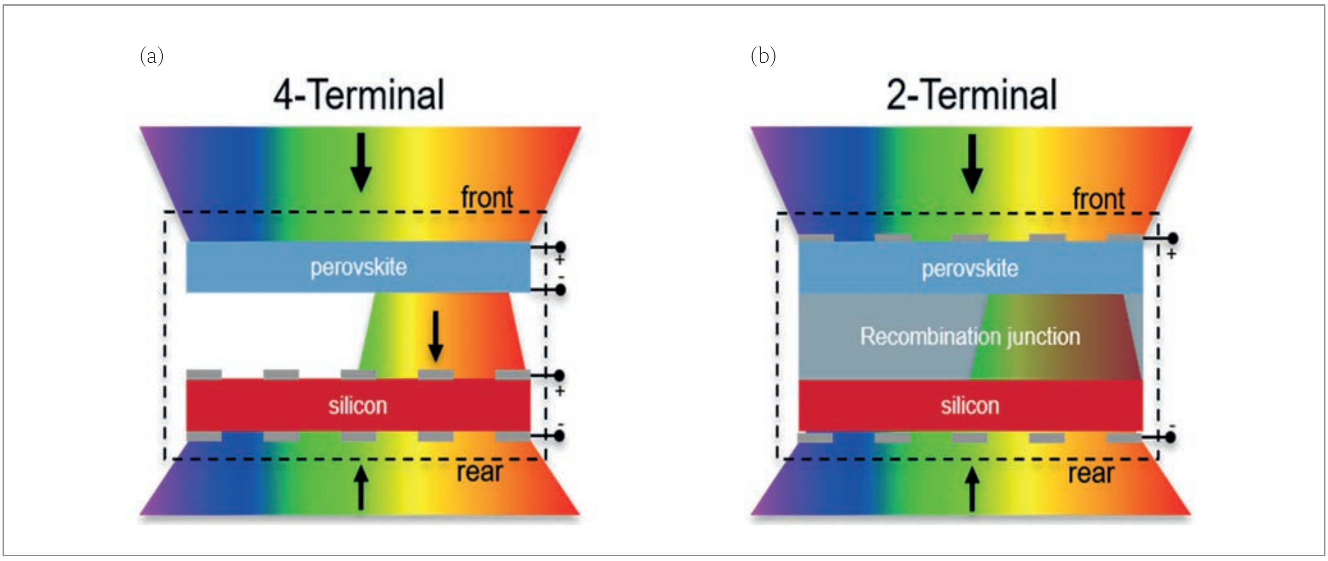

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Figure 9. Comparison of (a) 4T and (b) 2T bifacial tandem configurations. Photons incident on the front, and possessing energy below the perovskite band gap, reach the silicon bottom device and can be absorbed, while the entire photon spectrum incident on the rear is absorbed by the silicon bottom device. In a 4T tandem the extra rear incident light results in extra power being linearly generated. In contrast, the 2T terminal tandem device needs to be redesigned in order for there to be current matching of the two devices.

combination of silicon and perovskite devices for hybrid tandem modules. In a market where both technologies are rapidly developing, this can be a major advantage. In addition, the manufacturing operations are simplified because the two devices are optimized and classified separately, avoiding the propagation of any yield problems to the final tandem device.

The drawback is that the complexity is transferred from the manufacturing of the combined devices, as in a 2T configuration, to the module and system levels. Indeed, the interconnection of the respective separate arrays of the bottom and top devices in a module must take into consideration the characteristics of the two cell technologies: among others, silicon cell having high current and low voltage, while thin film having low current and high voltage as well as a different interconnection technology. It is likely that 4T tandems will require new module- and/or system-level power electronics. This explains how the complexity is transferred from the single-cell manufacturing to the module and to the system, which requires increased competencies during the system design and installation as well.

One of the advantages of a 4T configuration is the ease in building on major innovations in state-of-the-art perovskite and silicon PV technologies, such as bifaciality features. In a bifacial tandem module [33–34], the bottom solar cells (i.e. the silicon solar cells in this case) receive light from both sides. While the light received on the front of the bottom cell is 'filtered' (short wavelengths removed) through the perovskite top cell, the light entering from the rear is not. Nevertheless, its spectrum is affected by atmospheric scattering and reflection from surrounding surfaces. The rear incident light can have a dramatic impact on the design and operation of the tandem device.

> "The 4T bifacial tandem module can be considered a natural evolution of the performance limit of single-junction silicon-based module technology."

Consider the two major configurations: a 4T tandem and a 2T tandem (see Fig. 9).

Naturally, because of the absence of the need for current matching, 4T (and 3T) devices have the advantage of being suitable for bifacial operation [11]. In a 4T configuration the extra power generated by the bifacial bottom device scales linearly with the rear irradiance, and comes at almost no extra cost compared with a monofacial bottom device, except for the adaptation of the power electronics to the higher power. In a 2T configuration, however, the power production is limited by the requirement for current matching of the top and bottom cells. The performance of 4T and 2T bifacial modules in real-world operation (i.e. in yearly energy yield) has been compared by modelling [33]. While the bifacial 2T tandem device can be designed in such a way that the top device absorbs more photons in order to match the extra current generated in the bifacial bottom device (i.e. for approximate current matching in bifacial operation), this design is then only suitable for a limited range of rear irradiance levels (i.e. for a limited range of environment albedos and system geometries).

Several research groups have recently been working on 4T tandem cells and have reported impressive new findings. The degree of technology development varies, with device areas ranging from a few mm^2 to hundreds of cm^2. See Table 2 for a list of high-efficiency 4T tandem cells made of a single perovskite cell, typically of area 3×3mm^2. The top thin-film device (usually deposited on glass, as in the case of perovskite) is interconnected with typical thin-film module technology [35] combining

4T tandem	Description	Size [cm^2]	Efficiency top device [%]	Efficiency bottom device [%]	4T efficiency [%]	Power density Bifi200	Ref.
Solliance – TNO	Pk with MWT-SHJ – Bifacial	0.09	17.0	9.5	26.5	30.5	[34]
UoT – KAUST	Pk with SHJ	0.049	19.0	9.2	28.2	-	[37]
ANU	Pk with IBC Si	0.21	17.0	10.7	27.7	-	[38]
Solliance – imec	Pk with IBC Si	0.13	13.8	13.3	27.1	-	[39]
Solliance – TNO	Pk with MWT-SHJ	0.09	17.0	10.0	27.0	-	[40]
CAS	Pk with SHJ	0.1	18.3	8.7	27.0	-	[41]
FAU	Pk with PERL	0.1	17.1	9.6	26.7	-	[42]
Georgia-Tech	Pk with Topcon	0.06	17.8	8.9	26.7	-	[43]
KIT – ISFH	Pk with POLO-IBC	0.06	17.5	8.2	25.7	-	[44]
EPFL	Pk with SHJ	0.25	16.4	8.8	25.2	-	[45]

Table 2. High-efficiency 4T perovskite/silicon tandem cells.

laser isolation and conductive layer deposition and resulting in a thin-film module with very high voltage and low current. On a 100cm^2 aperture area, a perovskite module efficiency of 12% has been achieved in Solliance [36], resulting in a 4T tandem efficiency of about 20% when combined with an MWT-SHJ solar cell.

Despite the performance of the large-area tandem stacks not yet matching the performance of single-junction silicon devices, these initial large-area 4T tandem minimodules demonstrate the promising progress in scalability to industrially relevant areas. Most of the loss observed in the bottom device is due to the relatively lower transparency in the NIR region of the scaled-up device, since the highly transparent conducting oxides (TCOs) of the single cell reported in Table 2 have not yet been implemented in the top minimodule.

Challenges still remain; for example, a major hurdle to overcome is the integration of the bottom and top devices in a module that is capable of lasting at least 25 years, which is the minimum requirement in order to compete with state-of-the-art bifacial silicon modules. The manufacturing of stable, large-area, highly NIR-transparent and high-efficiency perovskite solar modules is the main challenge for the top device. Perovskites, because of the low cost of the constituent materials and the processing (e.g. solution-processed slot die coating, ALD and sputtering), are considered an ideal technology that can be produced at relatively low cost. When combined with the extra energy yield from bifacial configurations, the 4T bifacial tandem module can be considered a natural evolution of the performance limit of single-junction silicon-based module technology.

Industrial implementation

It is extremely challenging to bring new PV technologies to the market, even if only a few changes are made to the new product, compared with the standard. This has been the experience with bifacial PV. Since the start of the industrial workshop bifiPV2012, work has continued on several related aspects: developing standards, improving bifacial yield simulations, and carrying out more reliable calculations of bankability. These aspects will be targeted during the upcoming TandemPV workshops, but with a slightly different focus. Module lifetime and understanding of degradation mechanisms, as well as recyclability, will also be important aspects to consider when using more complex devices. Coupled assessments of energy yield and additional cost will allow effective evaluations of new tandem architectures [46,47].

The PV industry is a very special one in terms of bringing new products onto the market, because it is not only the cost but also the ongoing increase in lifetime and performance stability of the modules that must be considered. The recent consensus statement on the testing of perovskite solar cell stability [48] provides guidelines and reporting procedures based on the International Summit on Organic Photovoltaic Stability (ISOS) protocols, and represents a key milestone on the way to achieving a rapid industrialization pathway. As in the case of bifacial PV, in order to make the new tandem modules bankable, investors will first have to bring them into large PV fields themselves to prove to the banks that the promised theoretical yield and lifetime simulated through accelerated ageing tests can be validated under real-world conditions in large-scale systems. Only then will banks be willing to invest in large c-Si-based tandem PV systems, which will then allow a real commercial breakthrough of this promising technology.

Summary and outlook

A brief summary has been provided of some of the most important c-Si-based tandem structures with perovskites as the top cell absorber material. Depending on the evolution of the highly dynamic c-Si market, these tandem technologies will only have the chance to enter the PV market in the future if the most critical aspects are tackled now. For the roof-top market, the resulting modules do not have to be bifacial; however, if these tandem technologies are to enter the utility-scale and commercial roof-top market, bifaciality will undoubtedly be required. In the coming years, PV for the rapidly expanding field of commercial space applications will be revolutionized by using increasingly low-cost but high-efficiency modules, and c-Si-based tandem technology exceeding 30% efficiency could well be the winning choice in this case (using a p-type c-Si substrate because of better stability in space).

Whatever the future may hold for the dynamic and ever-evolving PV market, one thing is certain – c-Si-based tandem PV will play an important role, and it is anticipated that through this technology, PV cell and module production in Europe will be reinvigorated as well. With that in mind, the authors hope to see you at the TandemPV workshops (www.tandemPV.workshop.com) in the coming years, and look forward to working with you on creating the future of PV technology.

> “Tandem technologies will only have the chance to enter the PV market in the future if the most critical aspects are tackled now.”

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