Low-cost, high-efficiency solar cells for the future: ISC Konstanz's technology zoo

Joris Libal, **Valentin D. Mihailetchi** & **Radovan Kopecek**, ISC Konstanz, Konstanz, Germany

ABSTRACT

After several years of crisis, the PV manufacturing industry is expected to pick up again from 2014 onwards, and cell and module producers will consequently expand their production capacities in the coming years. To obtain high margins, producers must introduce new products that are better performing in terms of electrical performance and lifetime, even under harsh climatic conditions (e.g. in desert regions). This requires the use of innovative technologies that not only allow low production costs (US$/Wp), but also guarantee at the same time high module efficiencies and – even more importantly – high energy yields in terms of kWh over the entire lifetime of the system. This means that the most promising advanced cell concepts will use a limited number of standard industrial process steps and proven standard equipment. For at least the next five (probably more) years, high efficiency (>20%) at a reasonable cost will still be achieved with crystalline silicon-based technology alone. The research and development at ISC Konstanz therefore concentrates mainly on cell concepts that can be implemented using standard tube furnace diffusions and screen-printed metallization, with a focus on n-type-based technologies. This paper gives an overview of ISC Konstanz's technology zoo, including BiSoN, PELICAN and ZEBRA cell concepts, which are ready for industrial implementation. In addition, the integration of these innovative cells into modules, along with the importance of various features – such as bifaciality – in increasing the energy yield, is discussed.

Introduction

During the past three years the PV market has been extremely dynamic. On the one hand, module prices fell very quickly, making PV systems unexpectedly cost effective; on the other hand, the solar cell and module manufacturers fought for survival in the consolidating market, allowing prices to drop even faster – often even below production costs. Many companies became insolvent during this period, while some of the large ones stepped out of the business because of, for example, large losses and low expected margins in future sales. This hectic situation has slightly improved since the end of 2013, and PV producers in the cell and module sector are starting to realize profits once more.

During this long PV crisis, the main focus of the cell and module manufacturers was survival, by making their standard p-type c-Si products highly efficient and cost effective; many manufacturers were not willing to invest in novel technologies, although some of them have taken a small step forwards, implementing passivated-emitter-and-rear-cell (PERC) or metal-wrap-through (MWT) devices – concepts that are still based on monofacial p-type technology. A good overview of these technologies is given by Mack et al. [1].

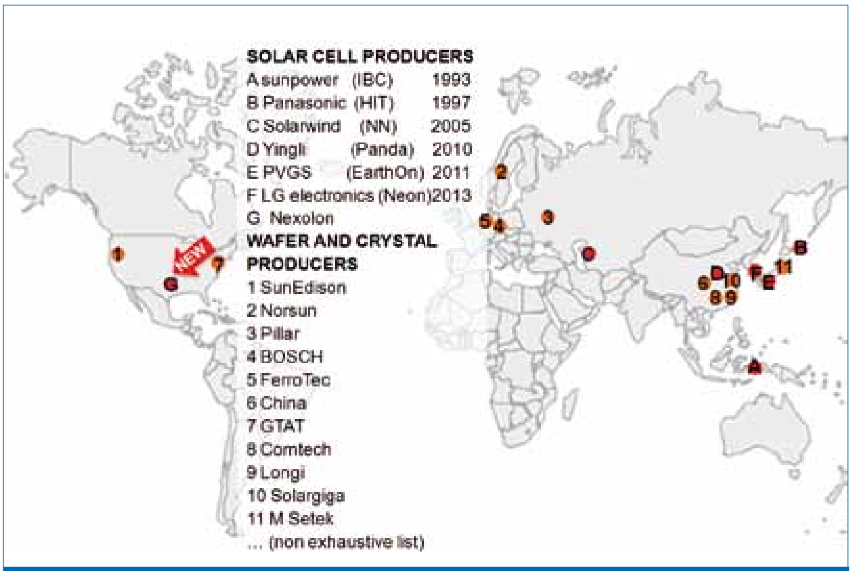

Figure 1. The major n-type solar cell and wafer manufacturers on the PV market in 2013.

The situation is currently changing, as innovations are now extremely important for the future ability of the still-existing companies to face competition on the market. The Chinese government is supporting this innovative spirit: efficiency limits have been set for new companies entering the market if they want to obtain governmental support. In addition, the current high balance of system (BOS) costs show very clearly that increased module efficiencies are necessary in order to make the whole PV system more cost effective, given the savings that have been realized on material and installation (i.e. area-related) costs from the BOS. This means that, in order to further reduce the system cost, the efficiency of solar cells must not be compromised by cheaper processes: consequently, the future is in the highest efficiency devices, mainly based on n-type c-Si technologies. Fig. 1 shows the worldwide distribution of n-type cell and wafer manufacturers on the market in 2013, along with the new ones that are just entering; it is expected that many others will follow in the next few years. These n-type technologies are scheduled to be discussed at the 2014 4th nPV Workshop in 's-Hertogenbosch (www.nPV-workshop.com).

> "The future is in the highest efficiency devices, mainly based on n-type c-Si technologies."

Another important technological benefit of n-type devices is that most of them are bifacial. Since module manufacturers are moving towards glass–glass modules anyway, the electricity harvest of a system can be drastically enhanced by using bifacial cells in such modules. Different bifacial technologies and the need for standardization in this area are topics for discussion at the 2014 2nd bifi PV Workshop in Chambéry (www.bifiPV-workshop.com).

Industrial solar cell concepts at ISC Konstanz

Many, if not all, solar cell manufacturers have very similar roadmaps to that of ISC Konstanz, as depicted in Fig. 2. In recent years ISC has developed solar cell concepts based on standard p-type c-Si technology with several structures and properties, as well as more advanced concepts based on n-type Si wafers. In order to categorize the solar cell concepts forming ISC Konstanz's technology zoo, names such as PELICAN, BiSoN, MoSoN and ZEBRA have been given to the different technologies. The efficiencies indicated in black in Fig. 2 show the current status, while those in white indicate the reasonable goals for 2014.

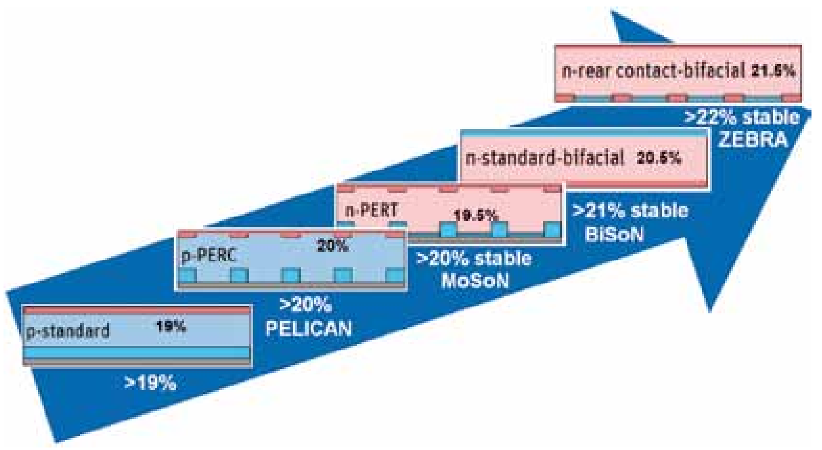

Figure 2. Roadmap of ISC Konstanz in regard to the different solar cell technologies and their efficiencies.

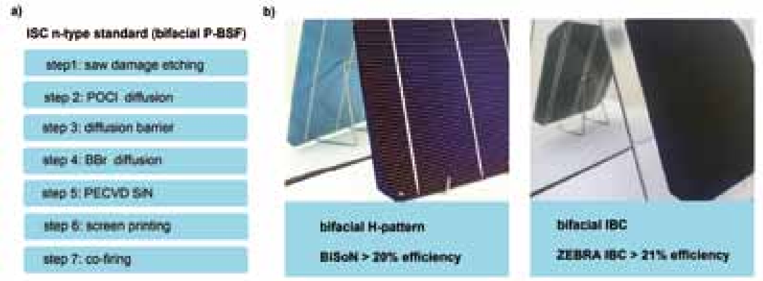

Figure 3. (a) BiSoN cell process flow; (b) photographs of bifacial BiSoN and ZEBRA cells.

The idea behind this roadmap is to be able to offer upgrades to every c-Si solar cell producer, no matter how far advanced it is with the technology in its production line. For example, if a 'standard solar cell producer' wants to upgrade to PERC, then PELICAN can be offered; if a p-type PERC producer would like to change to n-type technology, the most straightforward step would be to switch via MoSoN to BiSoN technology, gaining experience first with n-type substrates and B diffusion, and then with rear passivation and rear open contacts. The end of the roadmap – so far – is the n-type bifacial ZEBRA IBC (interdigitated back contact) technology, with the potential for efficiencies greater than 23% with diffused and greater than 24% with ion-implanted regions.

The parameters and corresponding references are summarized in Table 1. Compared with p-type, n-type concepts are better performing, since the n-type substrates not only have better properties (such as no light-induced degradation – LID – and better tolerance for prominent metallic impurities), but also show less degradation and are therefore more suitable for high-temperature processes, such as B diffusion. Other advantages of n-type concepts are summarized in Kopecek & Libal [2].

All ISC Konstanz technologies are based on standard industrial PV technology: c-Si 6″ wafers, tube furnace diffusions, passivations with different dielectrics and screen printing of metal contacts. Existing solar cell lines can therefore be upgraded for fabrication of the more advanced solar cell concepts just by including some additional (standard) equipment. In the case of PELICAN, MoSoN and ZEBRA, apart from some additional plasma-enhanced chemical vapour deposition (PECVD) capacity, a laser system for the ablation of dielectrics is needed. The processes are optimized, and industrially viable cleaning steps are selected and developed, since for high-efficiency devices the surfaces have to be very clean prior to the processing steps, such as B diffusion, P diffusion and passivation. The additional processes make the

Technology	Type	Area [cm^2]	*FF* [%]	J_{sc} [mA/cm^2]	V_{oc} [mV]	η [%]	η_{ave} [%]
Standard	p-type full Al	239	79.1	37.7	645	19.2	19.0
PELICAN	Cz-PERC full Al	239	80.1	38.1	653	19.9	19.8
MoSoN	n-PERT full Al	239	77.4	38.2	658	19.5	19.3
BiSoN	n-PERT bifacial	239	78.9	39.4	652	20.3*	20.0
ZEBRA	IBC bifacial	239	78.5	41.9	649	21.3	21.0

*confirmed by Fraunhofer ISE CalLab.

Table 1. Low-cost solar cells on 6″ wafers with industrial processes realized at ISC Konstanz.

fabrication more costly in terms of US$/cell; however, the cost of ownership (COO) calculations (summarized in the section 'Cost of ownership') show that the cell processes discussed here pay off in terms of US$/Wp at the module level, leading to even higher benefits at the system level (as discussed in the section 'Future systems'). Fig. 3 shows, as an example, the simplicity of the BiSoN process and photographs of the bifacial BiSoN and ZEBRA n-type solar cells.

Materials

Wafer

The worldwide distribution map in Fig.1 illustrates the increasing number of manufacturers which produce n-type wafers on an industrial scale. The wafer represents the most significant item of the cell production cost: it still remains a particular challenge to procure n-type wafers at a price which is comparable with that of p-type wafers. One reason why the production cost for n-type Si crystals is higher than for p-type is the lack of economy of scale in the case of n-type owing to the few cell manufacturers using n-type. Another factor that can potentially lead to an increased cost for n-type wafers is the high segregation coefficient of phosphorus (n-type dopant), which leads to a larger resistivity range over the crystal. For solar cell architectures that require a narrow resistivity range, the wafer yield can be significantly reduced. To resolve this issue, continuous Cz-pulling techniques have been developed, such as CCZ-Si by Sunedison, in which crystals grown using the CCZ-Si technique feature a narrow resistivity range for both p- and n-type. In addition, this technique is more cost effective than standard batch-type Cz-Si, because of the cost savings for consumable parts of the pullers (for details see Kearns [3]). Consequently, the CCZ-technique leads to a reduction in costs for high-quality p-type Cz-Si wafers as well.

> "The ZEBRA cell concept demonstrates constant high efficiencies for wafer resistivities between 3 and 14Ωcm."

Regarding n-type, another possibility for avoiding a potential yield loss due to a wide resistivity distribution is to develop cell concepts that are compatible with various wafer resistivities. As shown in Fig. 4, the ZEBRA cell concept demonstrates constant high efficiencies for wafer resistivities between 3 and 14Ωcm. In the case of the BiSoN cell concept, an increase in wafer resistivity leads to an increase in I_{sc}, while there is a slight decrease in fill factor (FF). Consequently, when integrating the BiSoN cells into the module according to an I_{mpp} sorting protocol, wafers with 2–10Ωcm resistivities can be used without any significant variation in cell (and module) efficiency. The cited resistivity ranges result in a high wafer yield, even for Cz-Si crystals grown by standard batch-type pulling.

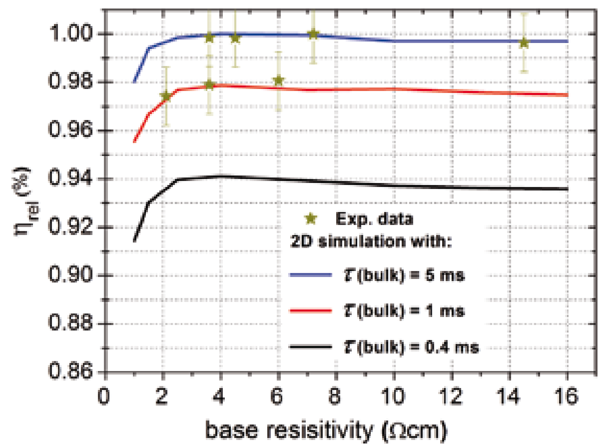

Figure 4. Experimental results and a 2D simulation of the relative efficiency variation of the ZEBRA cells as a function of base resistivity [4].

As regards the electrical quality, n-type Si is known to be more tolerant to common metallic impurities than p-type Si [5]. In combination with the absence of the LID caused by B–O complexes, this results in a high and stable minority-carrier lifetime compared with p-type Si. For this reason, the cell concepts with the highest efficiency potential – namely IBC and HIT – yield the best performance on n-type wafers.

Silver paste

The second most important item of the cell production cost is the metallization. The cost of current screen-printing technology is dominated by the cost of silver and the silver content of the paste used, and, of course, by the quantity of metal paste required for a particular cell concept.

Switching from the standard p-type Al-BSF (back-surface field) cell concept to advanced cell concepts, such as BiSoN or ZEBRA, basically means eliminating (cheap) Al paste and introducing (more expensive) Ag/Al paste for contacting the p^{+}-doped regions. Depending on the cell concept, it can be beneficial to combine a paste that is optimized for contact resistance with another paste that features a high lateral conductivity. If the contact geometry is optimized and state-of-the-art screen-printing technology is used, the metallization of advanced cell concepts can be implemented without increasing the production cost in US$/Wp at the module level, as demonstrated for BiSoN and ZEBRA cell concepts in the section 'Cost of ownership'.

Processes

As already mentioned, the applied processes are identical to those in standard p-type Si solar cell fabrication subject to a certain amount of tuning, along with some additional ones, such as advanced cleaning, BBr_3 tube diffusion, open rear-side Ag screen printing and (in the case of ZEBRA devices) laser ablation of dielectrics.

Etching, texturization and cleaning processes

The etching and texturization processes are very similar to those used for p-type processing. However, the fact that SiN_x is not etchable in NaOH allows the application of single-sided etching processes, for example to remove a diffused region from one side.

In order to obtain efficiencies above 20%, the surface pre-cleaning has to be better than that in standard processing. In addition, B diffusion takes place at higher temperatures, so metal contaminants must be removed from the surface more effectively. Such cleaning processes developed at ISC Konstanz are reviewed in Buchholz & Wefringhaus [6].

Diffusion and implantation

Since standard thermal diffusion processes (e.g. with $POCl_3$ and BBr_3 as dopant sources) using open tube furnaces are still adequate for achieving 21–22% efficiencies on a cell concept such as the ZEBRA IBC cell, these processes will continue to dominate, at least in the near future, because of their maturity, their cost effectiveness and, of course, the fact that the related production equipment is already present in existing cell-manufacturing facilities. However, since in the medium term the various roadmaps envisage efficiency targets of 23% in industrial production, it is expected that ion implantation will become more and more important. In fact, the values of the emitter saturation current J_{oe} required in order to achieve a cell efficiency of 23% are at a level that can be obtained, when using industrial processes, only with ion implantation. Important issues – apart from the equipment cost being still too high – are the optimization of the required annealing step, the tailoring of the doping profiles and the development of industrially viable masking processes. The EU-funded HERCULES project [7] aims to develop an IBC cell concept, and the related ion-implantation process, with a target cell efficiency of 24%.

Screen printing

Even though many innovative and promising metallization technologies have emerged in the last few years, the PV industry is still confident that screen printing of Ag-containing pastes will continue to play an important role, even when a timescale of 5 to 10 years is considered [8]. This is most likely due to the significant progress that has been made in screen-printing technology in the field of fine-line printing: 40-micron finger widths are now industrially feasible using double screen printing of Ag pastes [9], leading to higher efficiencies (as a result of reduced shadowing losses) and lower costs (because of reduced Ag consumption).

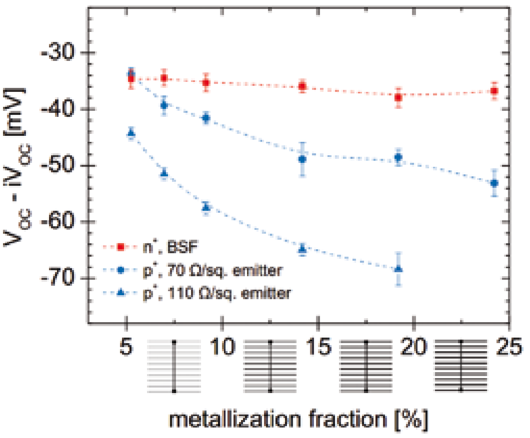

Figure 5. Net loss in cell V_{oc}, with respect to the implied V_{oc} value measured before metallization, as a function of screen-printed metal fraction on either a p^+ emitter or an n^+ BSF bifacial BiSoN cell.

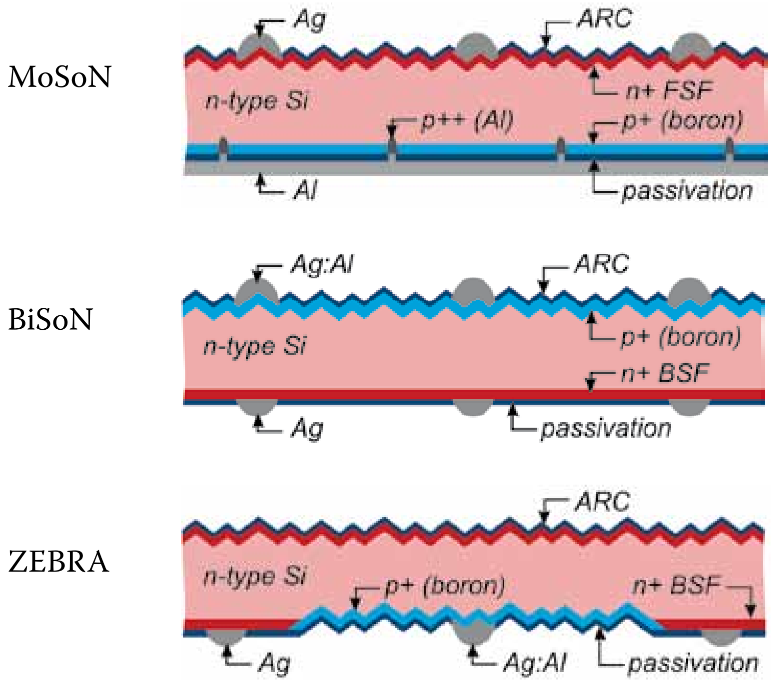

Figure 6. Detailed device cross sections of n-type concepts MoSoN, BiSoN and ZEBRA.

When considering cell concepts with a potential for high open-circuit voltages V_{oc} (e.g. BiSoN and ZEBRA), the use of currently commercially available screen-printing pastes represents a limiting factor for the effective V_{oc} that can be achieved in the final solar cell. This can be explained by the fact that during the firing process, metal penetrates the emitter and the space charge region, creating recombination centres and consequently increasing the J_{oe} [10]. For a bifacial n-type cell such as BiSoN, this means that the V_{oc}, for example, of the final cell is 650mV compared with the implied V_{oc} (before metallization) of 680mV or higher. As shown in Fig. 5, this loss in V_{oc} can be influenced by varying the emitter profile as well as by varying the total metal fraction. Another possibility for reducing the detrimental effect of screen-printing metallization is the modification of the paste composition. This approach has been adopted by Samsung, resulting in an IBC cell with screen-printed contacts featuring a V_{oc} of 670mV [11].

Ablation of dielectrics

When using dielectrics as masking layers, advanced cell concepts such as MoSoN and ZEBRA also require some process steps for the ablation of these layers. This ablation can be done either by the application of etching pastes or by using suitable laser systems. While the lasers are expected to offer an advantage in terms of running costs, the etching paste will be cheaper when taking into account the initial investment for equipment.

Device structures

As already described, with the availability of upgrades on the market for p-type devices the production of these can be switched to n-type concepts. The simplest device is MoSoN and the most complex one is ZEBRA, as shown in Fig. 6.

A p-type PERC structure can easily be transformed into a B rear-emitter PERT concept, called MoSoN, with only the implementation of a B diffusion on the rear. The other processing steps remain unchanged; however, they have to be slightly adapted to the n-type device. With the implementation of MoSoN, a manufacturer has the easiest way of switching to n-type solar cells and benefits from higher and stable efficiencies because of the n-type substrate.

To reap greater benefits from the n-type substrate, both sides of the device have to be passivated by a dielectric, which results in the BiSoN device. The B emitter is then at the front, and the passivation layer is chosen to be a PECVD SiO_2/SiN_x layer because of its simplicity and stability. An AgAl paste is screen printed on the front; on the rear side, the device has a flat surface diffused in a $POCl_3$ tube furnace, passivated by PECVD SiN_x and metalized by screen-printed Ag paste.

One more step further along the roadmap results in the ZEBRA solar cell. The processing steps are similar to those for BiSoN, with the exception that the P and B regions have to be implemented alternately on the rear side. This can be done by using a diffusion barrier which is structured by a fast laser, as ~70% of the barrier has to be ablated. The passivations and metallizations are identical to those for the BiSoN device. To implement the busbars on the rear side there are several options, but the easiest one is to use an isolation paste which isolates every second finger underneath the busbar.

MoSon, BiSoN and ZEBRA – three industrially feasible devices which are diffused, passivated and screen printed on both sides – have the potential to achieve stable efficiencies well above 20%, with the ZEBRA device attaining 23%.

> “MoSon, BiSoN and ZEBRA have the potential to achieve stable efficiencies well above 20%, with the ZEBRA device attaining 23%.”

Standard and advanced module concepts

Interconnection

The types of technology that can be used for the interconnection of cells within the module do not depend on whether the cells are p- or n-type, but only on the cell architecture. Accordingly, the various solar cell concepts discussed above can be divided into two main groups: two-side-contacted cells (BiSoN, MoSoN and PELICAN) and back-contact cells (ZEBRA). The two-side-contacted cells can be interconnected by the traditional soldering of ribbons using the same standard equipment as for today’s mainstream p-type solar cells (Al-BSF and PERC). There are, however, several new and advanced interconnection concepts available, such as the gluing of standard ribbons using electrical conductive adhesives (ECAs) [12], multiwire technologies (e.g. Meyer Burger SmartWire [13] – Fig. 7), or the NICE module concept by Apollon [14] (which encloses the cells between two glass sheets under an inert atmosphere without any encapsulant, while the ribbons are connected to the cells by mechanical pressure alone). For those types of cell with an open rear-side metallization, all these interconnection technologies allow the fabrication of bifacial modules when using a transparent backsheet or glass on the rear side.

The back-contact cells (ZEBRA) can be interconnected by the soldering or gluing of ribbons: both of these options allow the fabrication of bifacial IBC modules. This can be done on an industrial scale by using dedicated tabber–stringers that are currently on offer or under development by various equipment manufacturers. Another option is the use of conductive backsheets, and a dedicated module manufacturing line has already been implemented on an industrial scale for the fabrication of MWT modules (e.g. Verschoor & Baake [15]). In this case the electrical interconnections are integrated within the backsheet and covered by an insulating layer that has openings corresponding to the respective contact points on the cells (Fig. 8). An ECA is then used to electrically connect the cells to the conductive backsheet. This technology features very low cell-to-module fill factor losses, while the manufacturing

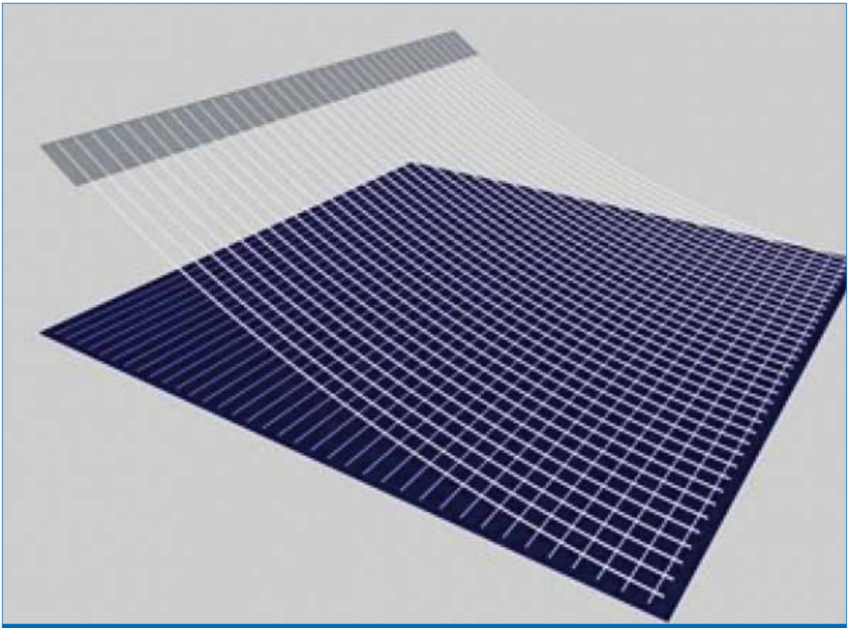

Figure 7. Schematic view of the SmartWire connection technology (SWCT) of Meyer Burger [13]: instead of interconnecting the cell busbars by means of two or three copper ribbons per cell, the busbar-less cells are interconnected by many thin wires.

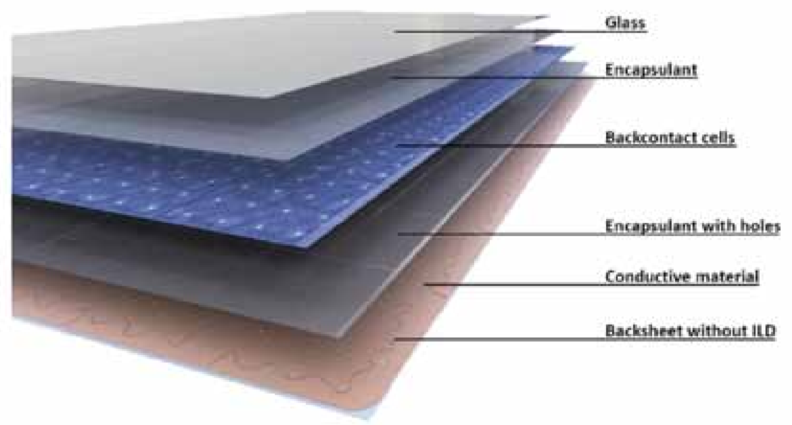

Figure 8. Cross section of an MWT module constructed with conductive backsheet technology [15].

lines are mostly suited to high throughput requirements (annual capacity over 150MW/year).

Encapsulation

Regarding the encapsulants, these must feature a high overall light transparency in order to transfer the maximum cell power to the module, i.e. achieve a minimum cell-to-module Pmpp loss. Because of the good spectral response in the UV range of the high-efficiency cells discussed in this paper, a high light transmission in the range 300–400nm is particularly important. As well as certain EVA encapsulants, alternative materials such as polyolefin-based sheets [16] and liquid silicone have proved to be satisfactory encapsulants with a high transmission in the UV range [17].

The light impinging on the area between the cells, as well as the light that crosses the entire solar cells without being absorbed, contributes to the optical cell-to-module losses. While the first component is also present in standard solar cells with a fully metalized rear side, the latter can cause significantly higher losses in bifacial cells. Consequently, when bifacial cells (BiSoN and ZEBRA) are integrated in monofacial modules, the use of highly reflective backsheets in combination with an optimized spacing of the cells helps to reduce the cell-to-module Pmpp losses: more light is reflected internally by the backsheet and therefore has a second chance of being absorbed by the solar cells.

Module lifetime

When carefully selecting the module bill of materials, today's industrial standards (80% residual module power after 25 years) can also be met using standard materials in the case of the advanced cell concepts discussed in this paper. Apart from keeping production costs as low as possible in order to reduce the module COO (US$/Wp), even for high-efficiency solar cells (see section 'Cost of ownership'), an increased module lifetime is another important factor that further reduces the levelized cost of energy (LCOE) for PV-generated electricity. In fact, using glass sheets instead of polymeric materials on the rear side of the modules, in combination with long-lasting encapsulant materials (e.g. certain silicone materials or no encapsulant at all, as in the case of the NICE concept), promises to deliver module lifetimes approaching 40 years or more.

Cost of ownership

At ISC Konstanz a comprehensive COO model for cells and modules has been created: this includes updated data regarding the cost and consumption of consumables as well as information about the CAPEX requirements for setting up the manufacturing lines for the various technologies. Among the various cost factors that have to be specifically adapted to the geographic location of the manufacturing site, the most prominent relate to energy (electricity, heating and cooling) and labour.

Another factor that can have a significant impact on the COO – in particular for the cell component – is the depreciation of equipment and buildings. Considering as a benchmark the standard technologies already present on the market, there is a vast array of possible CAPEXs subject to depreciation, ranging from an already existing amortized plant with standard technology (zero depreciation), to a completely new manufacturing line built from brand-new equipment (including the additional equipment for the advanced cell concepts, potentially requiring new equipment for the module line in the case of back-contact technology).

In order to correctly take into account the increased efforts in equipment spending for the advanced cell concepts, and in view of the fact that the concepts discussed herein can all be implemented as upgrades of existing standard p-type lines, the standard line (including factory building) has been considered amortized (no depreciation),

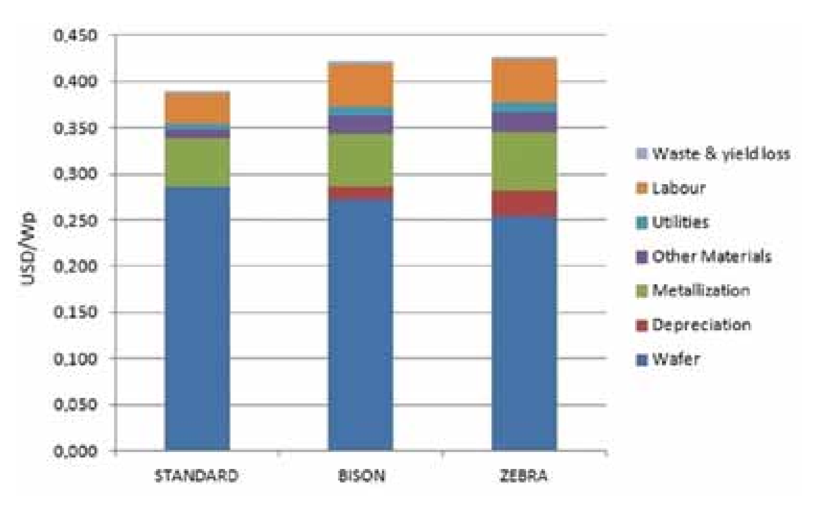

Figure 9. US$/Wp processing costs at a Chinese factory for p-type standard (Al-BSF) monocrystalline silicon cells compared with n-type BiSoN (bifacial, two-side-contacted) and n-type ZEBRA (bifacial back-contact cell) technologies. (Costs of US$1.3/wafer for 6″ p-type Cz-Si wafers and US$1.4/wafer for n-type wafers are assumed.)

while for the BiSoN and ZEBRA cells only the additional equipment and corresponding factory floor space has been taken into account. Under these assumptions, the COO calculations for a cell factory located in China (Chinese labour and energy cost) were performed at ISC Konstanz: the results are presented in Fig. 9.

> “For the move from BiSoN to ZEBRA, the cost of further process steps is offset by the higher cell efficiency.”

The use of mature industrial process steps for the implementation of a high-efficiency cell concept minimizes the technological risk but requires an additional cost for equipment, labour, consumables and energy, which means an increased production cost per cell. As shown in Fig. 9, this additional cost leads to a higher US$/Wp when changing from standard to BiSoN, whereas for the move from BiSoN to ZEBRA, the cost of further process steps is offset by the higher cell efficiency. When this is examined at the module level (Table 2), the picture is quite different: because the module production cost (excluding cell cost) is more or less fixed independently of cell efficiency, the production cost for the high-power modules made from the advanced cells is only slightly (3–4%) higher than the cost for the standard cell modules.

As illustrated in Fig. 10, this affords the possibility of selling modules with a high efficiency (over 300W for a 60-cell module) at a price (US$/Wp) that is similar to the current market price of standard p-type monocrystalline modules (around 265W), thus offering very interesting market opportunities to cell and module manufacturers. From the point of view of the end customer, the moderate cost of high-efficiency modules contributes to a reduction in the cost of the installed PV system, and consequently to a decrease in the LCOE. It has to be mentioned that, in the COO calculations presented above, the fact that the BiSoN and ZEBRA cells are bifacial has not been taken into account. The benefits at the system level that can be realized from the use of high-efficiency bifacial modules will be discussed in the next section.

Future systems

BOS and LCOE

The overall objective of every R&D endeavour in the field of PV and related industrial projects for implementing new technologies is the continuous reduction of the cost of electricity generated by PV. The LCOE is defined as the total life cycle cost of a PV system (modules, BOS, maintenance, financing cost, etc.) divided by the total amount of kWh produced during the whole lifetime of the PV system. In recent years the reduction in the cost of an installed system has stemmed mainly from a significant drop in the price of modules and only partially from a cost reduction in the elements contributing to the BOS (inverters, installation cost, etc.). Although the rate of decrease in module cost has been markedly high for standard module technology, any future decreases are expected to be much slower. Consequently, decreasing the area-related BOS cost by increasing the module efficiency, while limiting the increase in module COO (US$/Wp), will become the most important option for further reducing the system cost (and consequently the LCOE) in the near future, as was shown to be the case for the BiSoN and ZEBRA technologies in the section ‘Cost of ownership’.

> “The most significant increase in energy yield can be obtained by the use of bifacial modules.”

Looking beyond the system cost, the increase in energy yield in kWh/kWp of a PV system under actual operating conditions is another approach to reducing the LCOE. The most significant increase in energy yield can be obtained by the use of bifacial modules: for example, the BiSoN and ZEBRA cells are bifacial and can thus be integrated in bifacial modules using transparent backsheets or glass on the rear side. When installed in a suitable configuration (high albedo from the ground, and optimized spacing between modules and/or cells), bifacial modules can yield a yearly energy production that is more than 20% higher than that of monofacial modules of the same size with the same front-side efficiency (see e.g. Sugibuchi et al. [18] or Eisenberg et al. [19]). Assuming that there is little or no increase in system cost in US$/kWp, a 20% increase in kWh results in a 17% reduction in LCOE, depending on the characteristics of the installation site. Another interesting application is the vertical installation of bifacial modules that are oriented in an east–west direction: in this configuration, bifacial modules feature an energy yield in kWh/kWp (kWp of front side) that can be 90% more than the energy yield from monofacial modules with an optimum tilt oriented towards the south [20]. Considering that during periods of high solar irradiation in certain regions with a high density of PV installations (Germany, southern Italy) the total electricity production exceeds total grid demand, the vertical installation of bifacial modules yields important benefits regarding the grid integration, as this set-up smoothens the peak of PV electricity production at noon and increases the electricity produced by PV in the morning and in the evening (‘peak shaving’).

Bifacial modules are also

particularly interesting for installations in desert regions. Fig. 11 shows an example of outdoor measurements performed at the ISC Konstanz testing and development site in El Gouna in Egypt (Fig. 12): these data show the solar irradiance measured over a period of 18 days on the front (red curve) and rear (blue curve) sides of a bifacial module installed above the sandy ground of the Egyptian desert. It can be seen that under these clear-sky conditions, peak irradiances of over 200W/m^2 (or more than 22% of the front-side irradiance) are obtained regularly.

Apart from the high albedo – which is beneficial for bifacial modules – desert regions feature a number of climatic characteristics that require a special design of the modules in order to guarantee a constantly high energy yield and a long module lifetime for PV systems installed in such harsh conditions. The high ambient temperatures demand that special attention be given to the temperature management of the module so that the operating temperatures are maintained below a certain limit. Furthermore, the strong UV irradiation is very punishing with regard to encapsulant lifetime. A particular issue is soiling by sand, which can greatly reduce the amount of light reaching the solar cells: under unfavourable conditions, the energy yield can be reduced by 35% or more (e.g. Ibrahim et al. [21]).

	Standard	BiSoN	ZEBRA
Cell efficiency	19.0%	20.0%	21.5%
Cell COO (US$/Wp)	0.39	0.42	0.43
Pmpp cell (Wp)	4.55	4.78	5.14
Cell to module (US$)	76	76	83
Pmpp module (Wp)	270.0	284.2	305.5
Module COO (US$/Wp)	**0.67**	**0.69**	**0.70**
Compared with standard		+3.0%	+4.4%

Table 2. COO calculation results for standard p-type monocrystalline silicon cell and module production compared with n-type BiSoN and ZEBRA technologies (monofacial modules).

Because of their high solar irradiation and the fact that these large areas of land cannot be exploited in other ways, the deserts in various regions of the world (e.g. MENA, South America, China) are increasingly attracting the attention of investors and the PV industry. For this reason, ISC Konstanz – in cooperation with institutes and companies in countries such as Chile and Egypt among others – is dedicating significant R&D resources to developing technical solutions for the design of modules that are high performing and long lasting when operating in the above-mentioned deserts.

Summary and outlook

As highlighted in this paper, solar cell structures are becoming more complex, resulting in higher efficiency devices, but not, however, an increase in cost per Wp. Because the installation surface area for such devices with equivalent power generation is decreased, the BOS cost is automatically reduced; if bifaciality is also considered, the costs for such a system can be decreased even further. Calculations reveal that in this case, if installing a large PV system in, for example, the Atacama Desert (Chile), the cost of PV-generated electricity can be reduced to US¢2–3/kWh [22].

It is therefore extremely important for future solar cell concepts not to compromise cell efficiency. ISC Konstanz has a roadmap that targets an efficiency of 24% by 2017 with the use of low-cost processes which can be incorporated into existing production lines (Fig. 13).

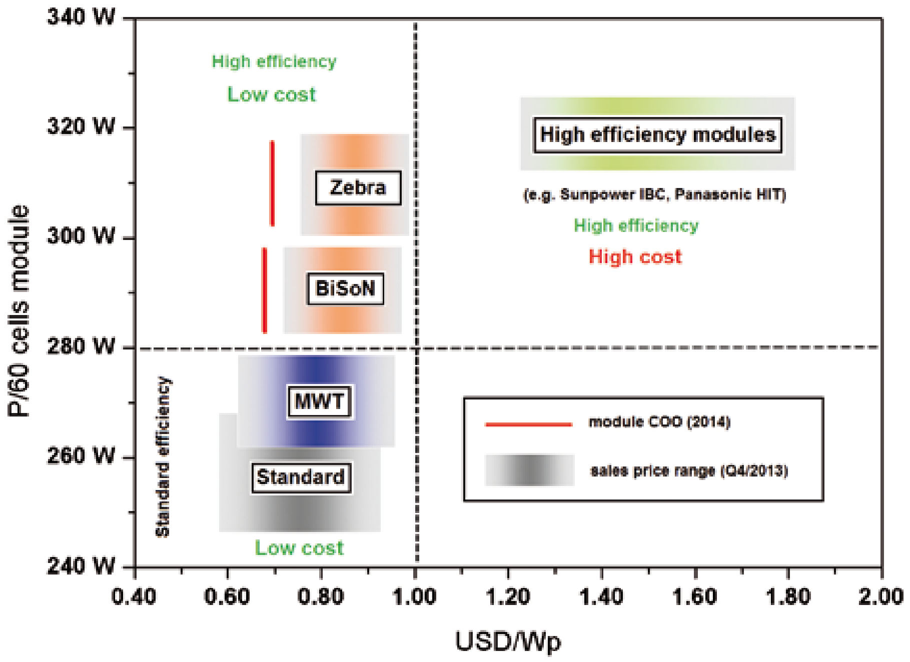

Figure 10. Efficiency (expressed as the Pmpp of a 60-cell module, assuming 6″ cells), COO and possible sales price ranges (US$/Wp) for BiSoN and ZEBRA modules compared with various PV technologies currently available on the market.

> “To compete with large Asian manufacturing lines in PV production, it is not only size but also advanced technology that matters in achieving higher module powers at similar costs per Wp.”

To achieve this roadmap goal, ISC Konstanz is participating in several EU and national projects, such as ModerN-Type, MetalTopp, HERCULES and 10ct, which all have in common the assembling of the pieces of the puzzle to create a 24%-efficient ZEBRA solar cell. In ModerN-Type (Eurostar E!7232), together with Eurotron, a rear-contact module concept is being developed based on conductive backsheet technology, whereas in MetalTopp (BMU FKZ 0325569B), screen-printing pastes are being developed for contacting p^+ surfaces with the aim of reducing the metallization-induced V_{oc} losses. In the case of 10ct (BMU FKZ 0325679B) and HERCULES (EU-GAN 608498), IBC technologies based on diffusion and ion implantation, respectively, are the focus. The plan to build a large 1–1.5GW factory in Europe, shared between France, Germany and Switzerland (similar to the Airbus consortium), was announced by French President François Hollande; this is considered to be predestined for implementing advanced low-cost technologies under development within the HERCULES project [7,23].

As demonstrated above, in order to be able to compete with large Asian manufacturing lines in PV production, it is not only size but also advanced technology that matters in achieving higher module powers at similar costs per Wp.

Acknowledgements

The authors thank their colleagues from the n-type group – A. Halm, G. Galbiati, A. Edler, C. Comparotto, L. Joseph and R. Roescu – as well as other ISC researchers and technicians who were involved in this work but not mentioned.

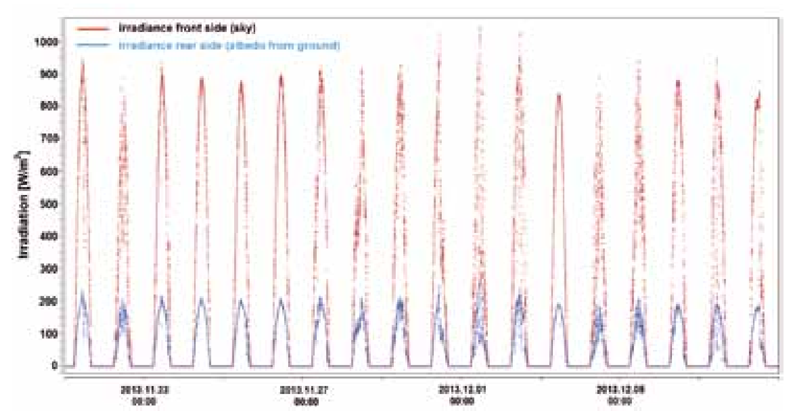

Figure 11. Outdoor measurements taken at the ISC Konstanz module test site: front-side (red) and rear-side (blue) irradiances measured on a bifacial module (20-degree fixed tilt) installed in the desert near El Gouna in Egypt.

References

[1] Mack, S. et al. 2014, “Technologies for mass production of PERC and MWT solar cells”, *Photovoltaics International*, 22nd edn.

[2] Kopecek, R. & Libal, J. 2013, “The status and future of industrial n-type silicon solar cells”, *Photovoltaics International*, 21st edn.

[3] Kearns, J. & Li, B. 2013, “Progress in n-type monocrystalline silicon for high efficiency solar cells”, *Photovoltaics International*, 21st edn.

[4] Galbiati, G. et al. 2013, “Si material requirements for high efficiency IBC solar cells fabricated using industrial applicable techniques”, 2nd Silic. Mater. Worksh., Rome, Italy.

[5] Macdonald, D. & Geerligs, L.J. 2004, “Recombination activity of iron and other transition metal point defects in n- and p-type crystalline silicon”, *Appl. Phys. Lett.*, Vol. 85, No. 18, pp. 4061–4063.

[6] Buchholz, F. & Wefringhaus, E. 2014, “Cleaning for high-efficiency solar cell processes”, *Photovoltaics International*, 22nd edn.

[7] Parnell, J. 2014, “French President calls for ‘Airbus’ style Euro solar manufacturer”, News Report [http://www.pv-tech.org/news/french_president_calls_for_airbus_style_euro_solar_manufacturer].

[8] Schubert, G. et al. 2013, “The future of metallization – Results from questionnaires of the four workshops from 2008 to 2013”, *Proc. 4th Metalliz. Worksh.*, Konstanz, Germany.

[9] Voltan, A. et al. 2013, “Development of metallization process for super fine line printing”, *Proc. 28th EU PVSEC*, Paris, France.

[10] Edler, A. et al. 2012, “On the metallization losses of bifacial

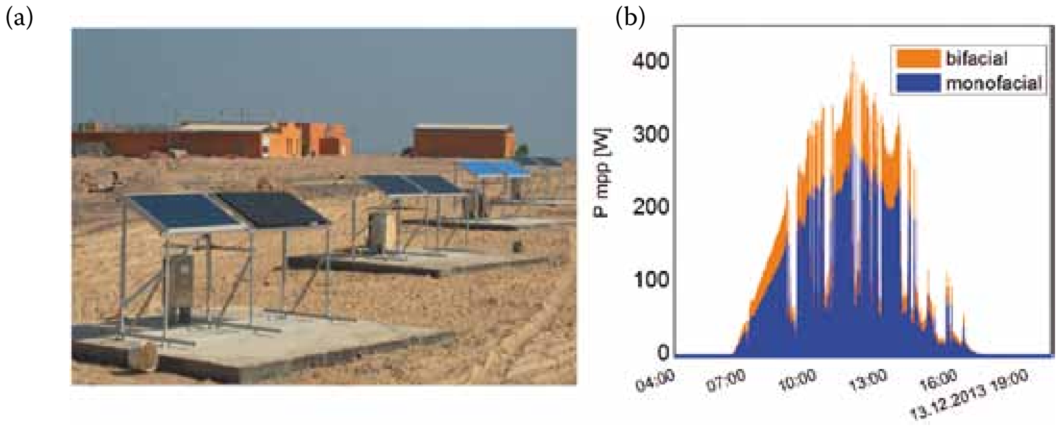

Figure 12. (a) ISC Konstanz module test site in El Gouna (Egypt); (b) Pmpp measurement of a bifacial module, reaching 400W around noon.

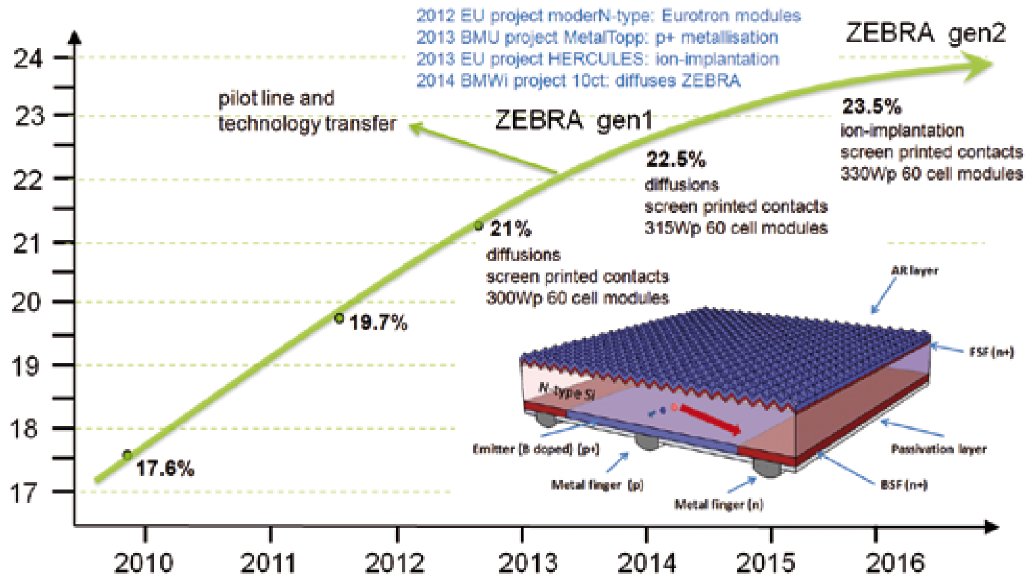

Figure 13. Efficiency roadmap for the ZEBRA solar cell.

n-type silicon solar cells", *Proc. 27th EU PVSEC*, Frankfurt, Germany.

[11] Kim, S.K. et al. 2012, "Exploiting metallic glasses for 19.6% efficient back contact solar cell", *Appl. Phys. Lett.*, Vol. 101, p. 064106.

[12] Chunduri, S.K. 2013, "Cool glue vs hot solder", *Photon International* (November).

[13] Osborne, M. 2013, "Meyer Burger offers fine-line copper wires connect for 5% higher power output of solar cells", Product Review [http://www.pv-tech.org/product_reviews/meyer_burger_offers_fine_line_copper_wires_connect_for_5_higher_power_outpu].

[14] Dupuis, J. et al. 2012, "NICE modules technology from the concept to mass production: A 10-year review", *Proc. 38th IEEE PVSC*, Austin, Texas, USA, pp. 3183–3186.

[15] Verschoor, B. & Baake, J. 2012, "(R)evolution of MWT module production", 4th MWT Worksh., Amsterdam, The Netherlands.

[16] Halm, A. et al. 2013, "Reducing cell to module losses for n-type IBC solar cells with state of the art consumables and production equipment", 3rd nPV Worksh., Chambéry, France.

[17] Ketola, B. et al. 2008, "Silicones for photovoltaic encapsulation", *Proc. 23rd EU PVSEC*, Valencia, Spain.

[18] Sugibuchi, K. et al. 2013, "Bifacial PV power output gain in the field using 'EarthON' high bifaciality solar cells", *Proc. 28th EU PVSEC*, Paris, France.

[19] Eisenberg, N. et al. 2012, "Outdoor bifacial module characterization: Power, energy generation and gain", bifiPV Worksh., Konstanz, Germany.

[20] Joge, T. et al. 2004, "Basic application technologies of bifacial photovoltaic solar modules", *Electrical Engineering in Japan*, Vol. 149, No. 3, pp. 32–42.

[21] Ibrahim, M. et al. 2009, "Advanced photovoltaic test park in Egypt for investigating the performance of different module and cell technologies", *Proc. 24th Symposium PV Solar Energy*, Bad Staffelstein, Germany.

[22] Metz, A. 2014, "Advanced characterization of solar cells and PV modules", 1st Worksh. Strateg. Solar Energy Basic Sci. Res., Santiago, Chile.

[23] HERCULES project [http://www.helmholtz-berlin.de/projects/hercules/].

About the Authors

Dr. Joris Libal works at ISC Konstanz as a research engineer, focusing on business development and technology transfer in the areas of high-efficiency n-type solar cells and innovative module technology. He received a Diploma in physics from the University of Tübingen and a Ph.D. in the field of n-type crystalline silicon solar cells from the University of Konstanz. Dr. Libal has been involved in R&D along the entire value chain of crystalline silicon PV for more than 10 years, having held various positions at the University of Konstanz, at the University of Milano-Bicocca and, more recently, as the R&D manager at the Italian PV module manufacturer Silfab SpA.

Dr. Valentin D. Mihailetchi joined ISC Konstanz in 2008 and is currently a senior scientist, leading the n-type solar cells group in the Advanced Cell Concepts department. He studied at the University of Groningen in the Netherlands; in 2005 he received his Ph.D. in physics, with the device physics of organic solar cells as his thesis topic. After that, Dr. Mihailetchi worked as a research scientist on crystalline silicon at ECN Solar Energy in the Netherlands, where he developed n-type-based solar cell processes for industrial applications.

Dr. Radovan Kopecek, one of the founders of ISC Konstanz, has been working at the institute as a full-time manager and researcher since January 2007, and is currently the head of the Advanced Solar Cells Department. Dr. Kopecek has also been teaching the basics of PV at the DHBW in Friedrichshafen since 2012. He received his Master of Science from Portland State University (Oregon, USA) in 1995, and then obtained his Diploma in physics at the University of Stuttgart in 1998. He completed his Ph.D. in 2002 in Konstanz, with a dissertation topic of thin-film silicon solar cells.

Enquiries

ISC Konstanz
Rudolf-Diesel-Straße 15
78467 Konstanz, Germany
Tel: +49-7531-36 18 3-22
Email: Joris.Libal@isc-konstanz.de
Website: www.isc-konstanz.de