Low-cost standard nPERT solar cells towards 23% efficiency and 700mV voltage using Al paste technology

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Abstract

Stable high voltages in solar cells and modules are becoming increasingly important as large PV systems are being set up in desert regions and are therefore exposed to high temperatures. High-voltage solar cells have lower temperature coefficients and thus produce a higher energy yield for such PV systems. Standard passivated emitter rear cell (PERC) devices have moderate voltages below 680mV, and also have the risk of degrading in such regions, because of light and elevated-temperature induced degradation (LeTID) effects and, in more recent observations, passivation degradation. This paper presents a solution for PERC producers to easily make the switch to n-type passivated emitter, rear totally diffused (nPERT) solar cells, which are capable of stable efficiencies above 22% and voltages close to 700mV, at almost no additional cost. This technology, called *MoSoN* (**Mo**nocrystalline **So**lar cell on **N**-type), merges the aluminium metallization technology from PERC with diffusion technology from nPERT (BiSoN). The adaptation of Al point contacts using the advanced Al-technology from Toyal for the rear side of the MoSoN cell leads to a rear point contact selective emitter and device voltages of around 695mV using n-type LONGi wafers. Further optimizations could even lead to voltages above 700mV. The cost of ownership (COO) is in the same range as that of standard PERC solar cells, even before the degradation in PERC has been taken into account, as the rear AlO_x (passivation) is replaced by BBr_3 diffusion (simultaneous diffusion and passivation by an in situ grown SiO_2 layer). In addition, no degradation of the passivating layers is observed in MoSoN cells, in contrast to PERC solar cells, where such effects have been recently observed.

Introduction

PV solar cell and module manufacturers are again finding themselves in a deep crisis. As in the case of the crisis that started in 2011, there is huge overcapacity, since the demand has not been growing as expected. At the end of 2018 a total production capacity of 160–170GW with a 60–70GW passivated emitter rear cell (PERC) capacity is forecast [1]; this will be about 60–70% above the actual demand in 2018. The shake-up continues, but now in Asia, as there are hardly any large manufacturers left in the EU or USA. The most-affected companies are those which focus on standard mc-Si Al-BSF technology. Fig. 1(a) shows the cell technology market share in 2018 and forecasts, indicating that in the next five years the future belongs to PERC technologies on p-type Cz-Si material.

“The degradation mechanisms in PERC remain very complex.”

One of the great things to come out of the first crisis was the rapid entry of new innovations into the PV market, such as PERC and n-type passivated emitter, rear totally diffused (nPERT) technologies. On the other hand, the speed of implementation of PERC technology has been so quick that not every PERC producer has keen insights into the actual challenges connected with this technology, such as light and elevated-temperature induced degradation (LeTID) [3,4] and, more recently, passivation degradation of the PERC rear side, observed by the University of Konstanz [5]. Whereas light-induced degradation (LID) is based on the formation of boron–oxygen complexes and can be suppressed by, for example, low oxygen material or by regeneration [6], LeTID is suspected to be the consequence of too much hydrogen in PERC being introduced to the Si-bulk from two-sided plasma-enhanced chemical vapour deposited (PECVD) SiN_x passivation layers [7].

Several solutions have already been proposed for reducing LeTID – for example, the use of low-hydrogen-content SiN_x layers, or the reduction of the metal contact firing temperatures in order to minimize the amount of hydrogen released into the bulk material [7]. Some PERC producers, with deeper insights into their products, use a combination of both the above, and select Si materials that are less affected. However, a certain amount of degradation can still be observed, even in such adapted solar cells, as the degradation mechanisms in PERC remain very complex.

In the authors’ opinion, one of the best and simplest options for non-degrading solar cell design is to switch directly to MoSoN (**Mo**nocrystalline **So**lar cell on **N**-type). This type of device is very similar to the existing PERC structure, with just two major feature differences: 1) a switch to n-type material; and 2) the addition of a BBr_3-diffusion step, instead of the more commonly used AlO_x passivation. N-type wafers are nowadays only 5% more expensive than p-type ones, but have the advantage of being more stable to the above-mentioned degradation mechanisms. This paper describes very briefly ISC Konstanz's MoSoN solar cell concept, summarizes the solar cell parameters achieved, compares the costs with standard PERC, and sketches out what such a switch from PERC to MoSoN could look like.

Fig. 2 shows the cross section of a MoSoN cell; it consists of an n-type PERT solar cell with a boron rear junction and Al metallization (similarly to PERC technology) on the rear side. By recrystallization of aluminium-doped silicon, a selective emitter is created locally beneath the rear-side contacts. The advantages of this solar cell concept will be described in the following sections.

Many scientists are saying nowadays that the 'next big thing' after the introduction of PERC and bifaciality will be TOPCon [8], by which they mean carrier-selective passivated contacts and a heavily doped silicon layer between the contacts and the wafer. Such passivated contacts can be processed in many ways, as summarized (for example) at EU PVSEC 2018 by Cuevas [9]. As PV is more an evolutionary industry than a revolutionary one, in the authors' opinion there is still at least one step in between, namely the low-cost and stable n-type Al paste technology, with efficiencies reaching 23% (nPERT) and above (IBC) and voltages of around 700mV.

Fig. 3 shows a summary of ISC Konstanz's status, along with a roadmap, for the dominating c-Si technologies.

Standard Al-BSF technology, shown in Fig. 1 in the lower left corner, is losing market share in favour of PERC solar cells. Not only that, Al-BSF standard solar cells are limited to efficiencies of around 20%, and Al-BSF technology cannot even be adapted to bifacial application. In contrast, PERC solar cells can be produced for bifacial application and will boost the bifacial market, as bifacial PERC modules can be offered at almost the same price as monofacial ones. Going bifacial will save Al paste; however, the front-side efficiency will consequently be partly cannibalized by 0.2–0.4%$_{abs}$, depending on the bifaciality factor, which is typically between 65 and 80% [10]. Standard front-emitter nPERT technology (BiSoN in ISC's case) produced by, for example, Yingli, Jolywood, REC, Adani, Linyang and others, can yield the same efficiencies as bifacial PERC but at higher bifaciality factors, ranging from 85 to 95%. The highest and most stable efficiencies with diffused junctions can be achieved with rear-

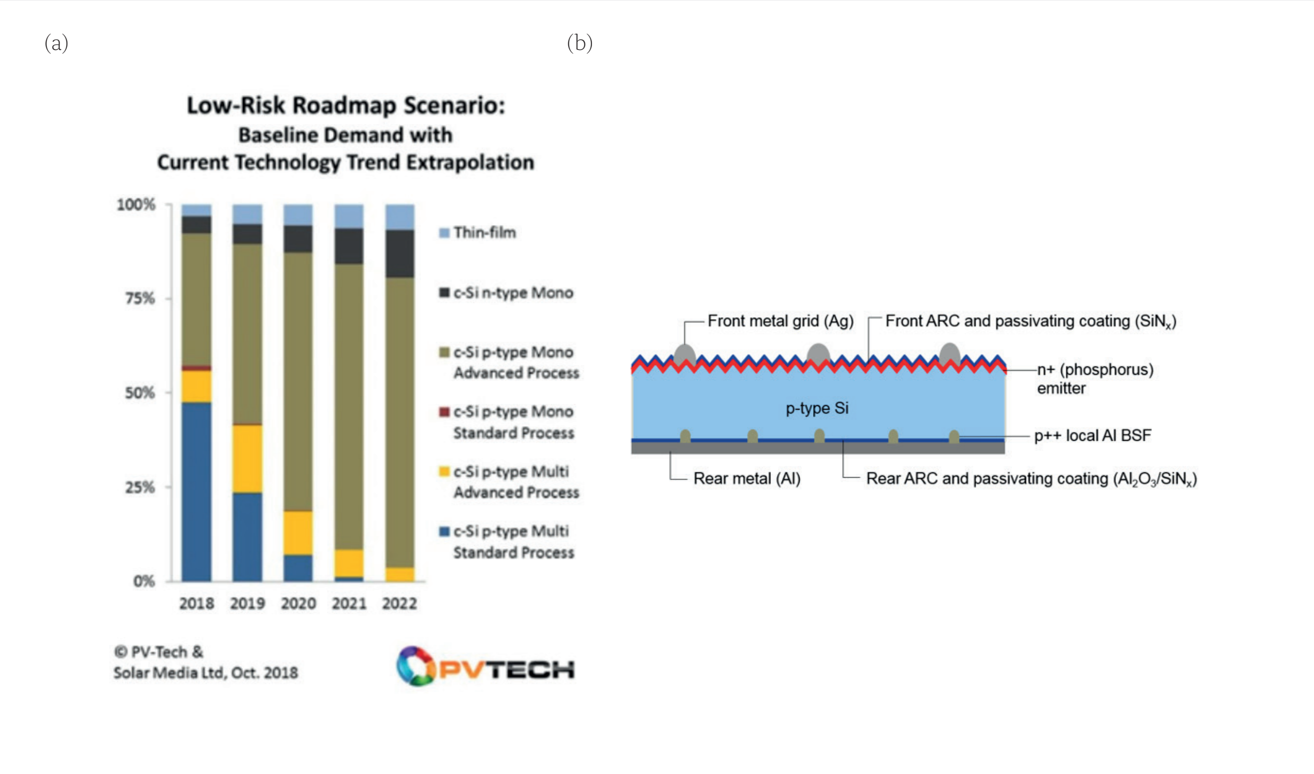


Figure 1. (a) Forecasts of technology shares (from PV Tech [2]); (b) a typical cross section of a p-type PERC solar cell.

emitter Al paste nPERT technology (MoSoN) and IBC technology (ZEBRA).

Efficiencies with MoSoN currently stand at 22.2% (22.98 with 0BB) – and with ZEBRA at 23.2%. In addition, Al paste technology will be introduced to ZEBRA and BiSoN in the coming months, and the V_{oc} is expected to be boosted to around 700mV. In the case of BiSoN, this will be a bigger challenge, as the Al paste will be used for the front side, where thinner contacts need to be printed, something that is not trivial for Al paste technology at the moment. Dielectrics laser opening technology as well as advanced Al paste from Toyal will be used, in addition to Toyal's optimized firing-through Al paste.

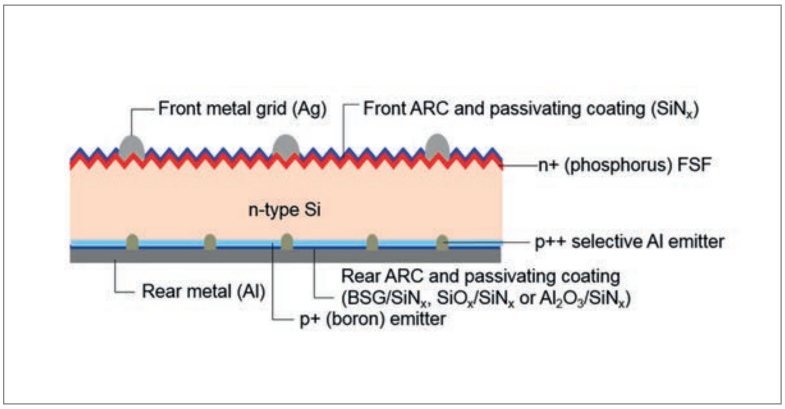


Figure 2. Cross section of a MoSoN solar cell.

Status of PERC solar cells and possible degradation mechanisms

PERC solar cells are rapidly becoming the new standard – the question is whether this is happening too quickly in some cases.

Status of PERC

PERC is a mature technology with a relatively simple process, and therefore also with a low cost of ownership (COO) atttached. With PERC technology, a record efficiency (at the time) of 23.6% was achieved by LONGi [11] (March 2018) with a busbar-less metal contact design, which was later surpassed by JinKo with 23.95% [12] (May 2018). Record efficiencies are nice; however, what counts is the average values in production and the stabilities over time. For the big players (Hanwha Q CELLS, JA Solar, LONGi, TRINA, JinKo, Canadian Solar, etc.), average efficiencies these days in production are between 21.5% and 22%; this is outstanding compared with standard Al-BSF technology, which has dominated the market for decades and for which the best average efficiencies hardly exceeded 20%. With regard to degradation, however, it is not certain if all PERC producers have understood the challenAges of coping with all these types of effect that this device can additionally suffer from.

Degradation of PERC

When visiting conferences and manufacturers, it is often surprising to see how many people responsible for PERC modules have never even heard about the severe degradation problems that can affect PERC devices – in particular when talking about LeTID (alias 'carrier-induced degradation' – CID). Even at the 4th PERC Solar

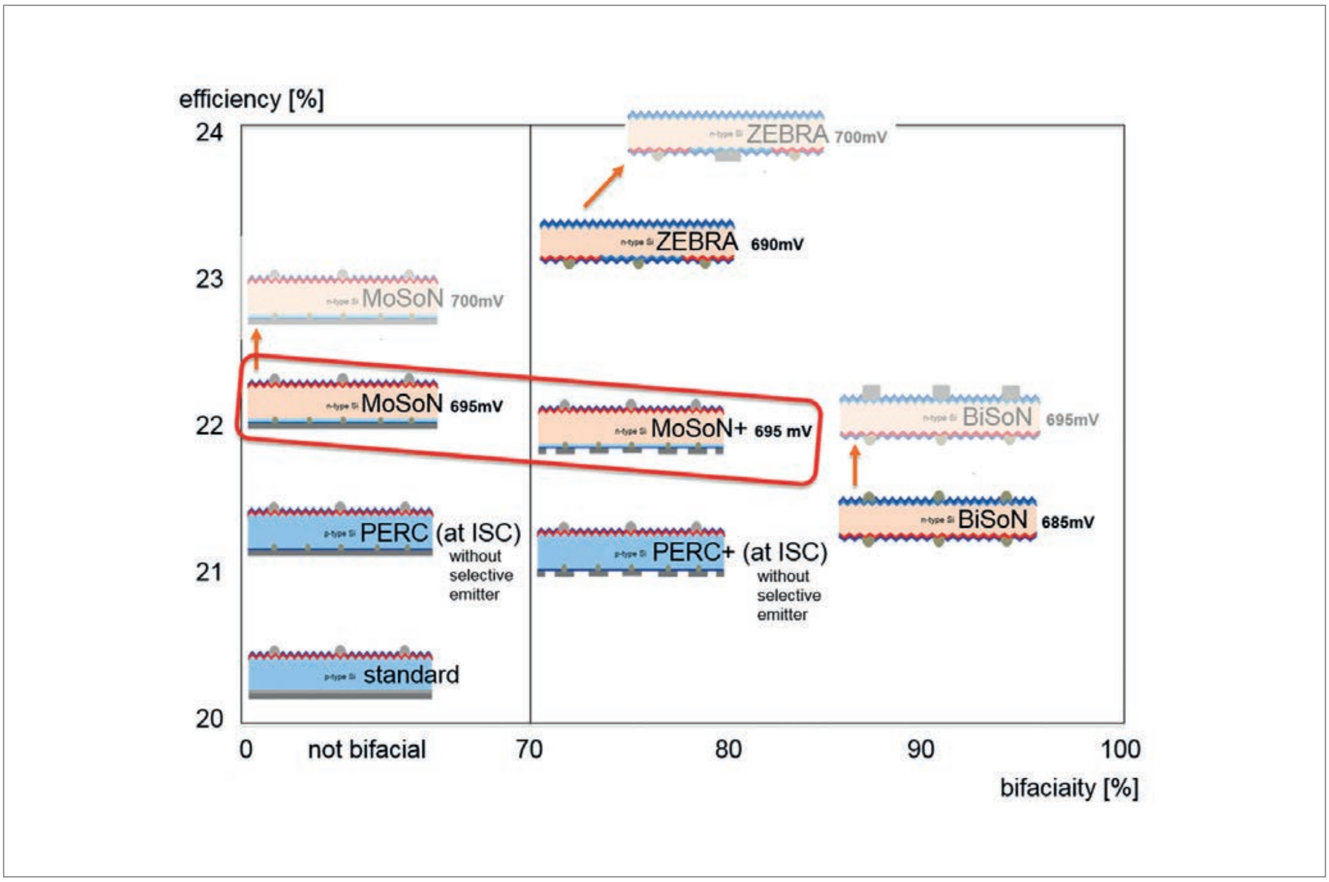


Figure 3. ISC Konstanz's status and roadmap for standard diffused cell technologies.

Cell and Bifacial Module Forum 2018 [13], LeTID was not really one of the topics. A common response to LeTID that can be heard is: "LeTID? No – we have no LID: we are stabilizing." Or, some – who are more informed – say: "LeTID only impacts mc-Si PERC – we produce Cz-Si PERC." Neither of these statements is true. Even if LeTID was first observed on mc-Si PERC cells [3], the effect is also visible and detrimental in the case of Cz-Si PERC modules [4], where it can be very severe. In this regard, PI Berlin has tested (and continues to test) for LeTID in many of the PERC modules available in the market. After six weeks of exposure to accelerated degradation, all the tested modules (around 10 so far) had degraded by 5% relative or more in terms of power – and the degradation curve did not appear to have reached saturation. Furthermore, there are stories of PERC PV systems 'out there' where the modules have degraded to close to 20% after 2–3 years' operation, which is simply a tragedy.

Status of PERT solar cells and degradation mechanisms

Status of PERT

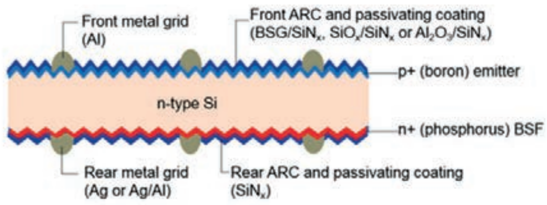
There are two different PERT approaches, of which currently only the Afront-side emitter approach is commercially produced (e.g. by Jolywood, REC, Yingli, Adani, Linyang and others). A good summary presentation at EUPVSEC 2018 was given by Tous from imec [14] on the lab results for both technologies, from which a selection of the achieved efficiencies is cited in Fig. 4 (in the paper, all groups are referenced). The efficiencies marked with * are those certified by calibration labs.

The highest efficiencies were achieved with the rear-emitter nPERT concept, with 23% achieved by imec. It has to be noted that many different techniques are used in both technologies – even passivated contacts as of now, with plating procedures and zero-busbar technology measured by Grid^{TOUCH}. ISC Konstanz's strategy is to use only processes which are currently employed in industry. At the time of the presentation by Tous [14], with ISC Konstanz's MoSoN concept an efficiency of 21.8% [15] had been achieved, which was confirmed by FhG ISE CalLab (shown later in this paper, in Fig. 8). Recently, 22% has been surpassed and 693mV achieved with a homogeneous front-surface field (FSF) and standard screen-printing technology (see later, Table 1). Details of this technology will be discussed later.

Degradation of PERT

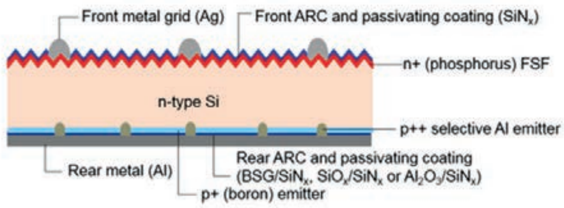
Much less degradation occurs in n-type devices; however, some scientists have claimed that LeTID can also impact nPERT and IBC solar cells. Such studies are currently being carried out at ISC Konstanz: no noticeable decreases in the cell parameters have been observed. In the past, scientists have also seen UV degradation

(a)



eta [%]	j_{sc} [mA/cm^2]	V_{oc} [mV]	FF [%]	BSF Type	BSF formation	metal. front / rear
22.8	40.5	694	81.1	sel.	$POCl_3$ + laser doping	0BB NiAg / NiAg
22.6*	40.8	698	79.3	hom.	PECVD n-poly	0BB SP-Ag / SP-Ag
22.4*	40.0	688	81.4	hom.	n.p. n-poly	SP-Ag / SP-Ag
21.8*	40.3	673	80.3	hom.	Implant	5BB SP-Ag / SP-Ag

(b)



eta [%]	j_{sc} [mA/cm^2]	V_{oc} [mV]	FF [%]	FSF type	emitter formation	metal. front / rear
23.03*	41.1	683	82.0	sel.	BBr_3	0BB SP-Ag / SP-Al
22.9*	40.9	705	79.4	sel.	BBr_3	0BB NiCu / PVD Al
22.5*	40.2	700	79.9	sel.	epitaxy wafer & p^+	3BB NiCu / PVD Al
22.3*	38.5	714	81.1	hom.	LPCVD n-poly	0BB SP-Ag /ITO+SP-Ag
22.0*	39.7	685	80.9	sel.	APCVD BSG	3BB NiAg / SP-Al
21.9	40.5	669	80.9	hom.	BBr_3	5BB SP-Ag / SP-Al
21.78*	39.5	686	80.4	hom.	BBr_3	5BB SP-Ag / SP-Al

Figure 4. Solar cell parameters for two different nPERT technologies: (a) front emitter; (b) rear emitter (tables from Tous [14]).

in oxide-passivated B-emitter solar cells, which was based on the migration of B dopants into the oxide, creating a stronger depletion layer [16]. In all ISC Konstanz's cell concepts, however, an in situ grown SiO_2 passivation layer is used on the B emitter during the BBr_3 diffusion [17]; therefore, this layer is already saturated with boron, and the depletion regions at the Si surface are not increased. No such degradation has been observed so far in all the cell concepts, such as BiSoN, MoSoN and ZEBRA.

Advanced aluminium paste technology

The idea behind MoSoN (and other rear-junction nPERT technologies) is to combine n-type, which offers high and stable efficiencies, with Al paste contacting technology. In this technology, for nPERT rear-junction devices, selective emitters are created during Al recrystallization and the is increased. If the contact area is minimized to a region of small dots, one can get very close to the passivated contacts by minimizing the total contact area to less than 1% (see Fig. 5). Such small contacts can, in principle, be easily contacted by aluminium, provided proper alloying is realized by adjusting the paste chemistry, including the glass frit and boron content in the paste. Additionally, the smaller the size of the laser contact opening (LCO), the stronger the out-diffusion of silicon from the wafer to the paste during alloying, and the lower the rate of the out-diffused silicon returning to the wafer during the cooling-down, to form the required locally alloyed emitter. Toyal have developed an Al paste which can be used for the generation of small local emitter points and contacts by adjusting special Al-Si alloy and Al powders in the paste, opening up new horizons in low-cost metallization of MoSoN solar cells.

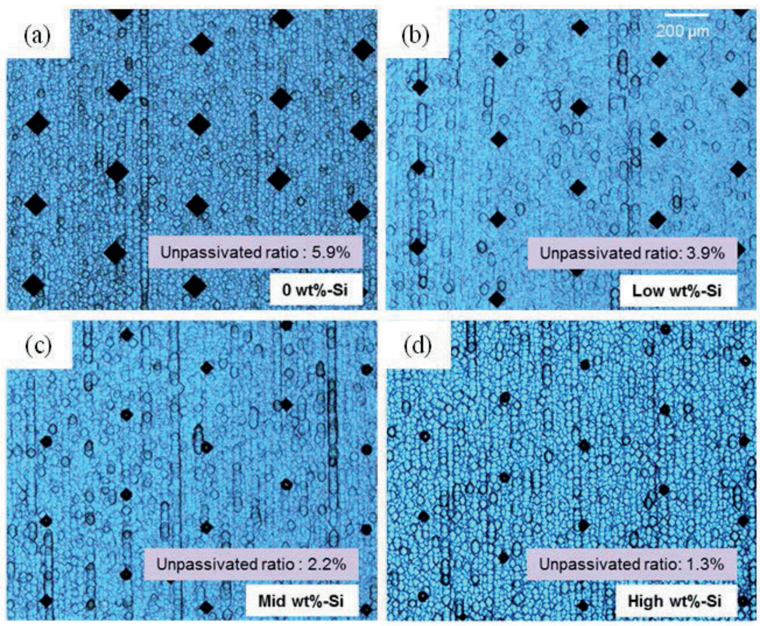


Figure 5. Creation of small point contacts as a function of the Si content in Toyal's Al paste [15].

> "The idea behind MoSoN is to combine n-type, which offers high and stable efficiencies, with Al paste contacting technology."

Aluminium-contacted homogeneous and selective rear-emitter PERT solar cells

The aim of MoSoN is to reap two advantages:

1. The lower degradation sensitivity of n-type material.
2. The low-cost and high-voltage contacting properties of Al paste.

The history of rear-junction nPERT technology extends over more than 10 years, as illustrated in Fig. 6.

At the beginning, in the case of the so-called 'Phos-Top concept' at the time, the emitter formation was performed using Al paste only, but very soon this became a combination of boron diffusion with Al paste technology, which was investigated in detail by Hanwha Q CELLS. The potential of these solar cell concepts is still very high, as the process is extremely simple and results in stable and high efficiencies. ISC Konstanz has therefore been working on such a concept – namely MoSoN – for a long time, within the scope of several national and industrial projects.

Fig. 7 shows the process and the cross section of MoSoN technology. The process begins with saw-damage etching. This is followed by both-side boron diffusion, during which the rear surface is already passivated by an in situ grown SiO_2 interface layer, and so no AlO_x passivation is required. SiN_x is then deposited on the rear side, and the wafers are textured on the front side. After a $POCl_3$ diffusion process, the front-side SiN_x is PECVD deposited, and the rear SiN_x opened by a fast laser. Subsequent to metallization and firing, the finished devices are edge isolated. Currently, work is also under way on wet-chemical edge isolation, which will be implemented in the near future.

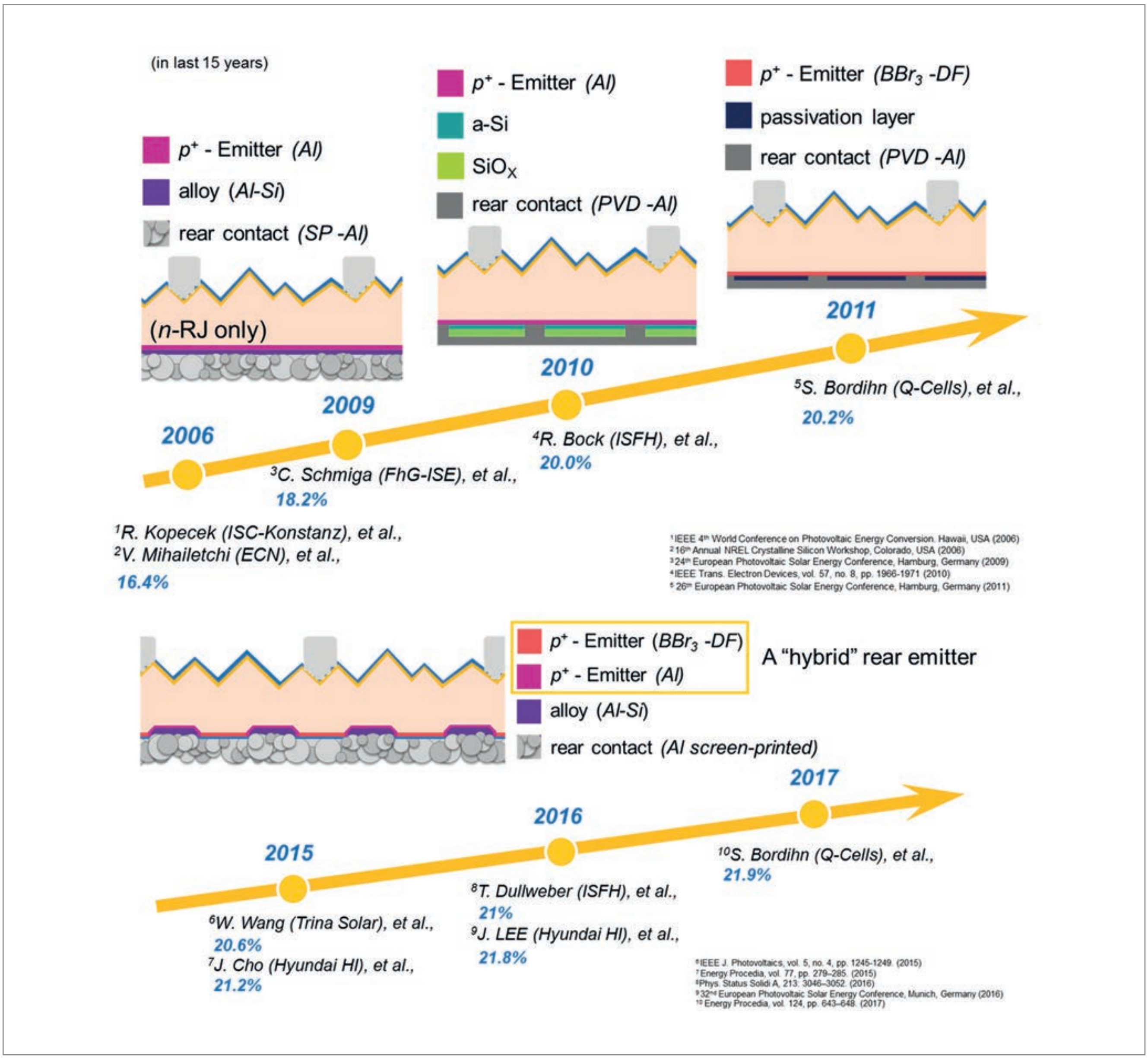


Figure 6. History of rear-junction nPERT technology [15].

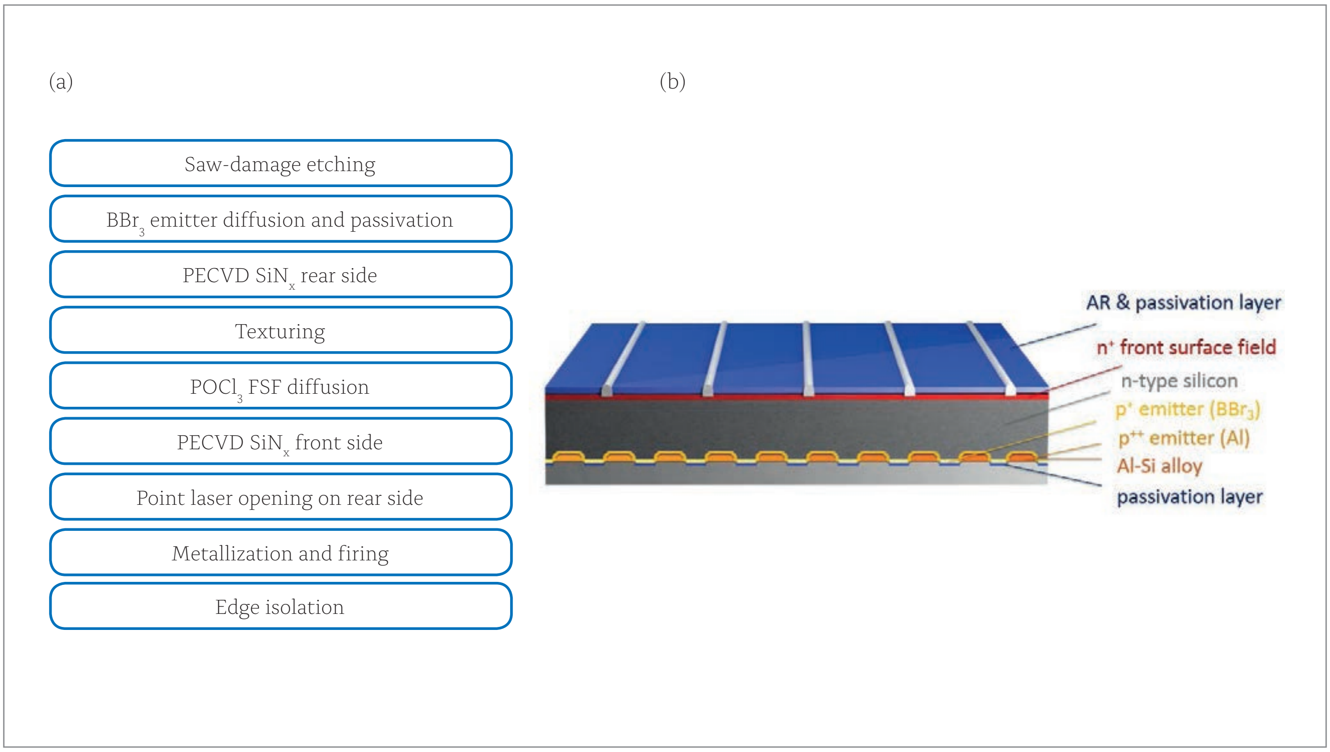


Figure 7. MoSoN solar cell: (a) process flow chart; (b) cross section.

It has to be noted that the rear PECVD SiN_x layer is included in a high-temperature diffusion process, resulting in a very low hydrogen content, which might explain why no LeTID is observed for MoSoN cells. Fig. 8 shows the *I–V* measurement of a 21.8% cell, certified by FhG ISE CalLab.

The high efficiency is excellent, but what is remarkable here is the very high voltage of 686mV without a selective FSF and without passivated contacts. The MoSoN development at ISC Konstanz is focused on achieving high voltages with very simple 'close to standard' processes. The most recent cell parameters resulting from the development with optimized point contacts, which resulted in an efficiency of 22.2% and an outstanding voltage of 693mV, are summarized in Table 1.

The bifacial cells, with (so far) a moderate bifaciality factor of 60%, resulted in efficiencies of 22%; experiments are under way in an attempt to achieve 700mV and 22.5%. MoSoN solar cells with zero busbars (0BB) yielding 22.98%, measured by Grid[TOUCH], were recently processed (J_{sc}=40.7mA/cm^2, V_{oc}=693mV, FF=81.5%); this efficiency corresponds to the highest achieved by imec from the table in Fig. 4(b). The MoSoN concept will be presented at the centrotherm booth and during an invited talk at the 2019 SNEC PV Power Expo.

Table 2 summarizes the advantages of the MoSoN solar cell compared with standard PERC devices.

The process for MoSoN does not include selective FSF, and so the front-side process is simpler than that for many PERC record cells. The efficiency potential in production is higher for MoSoN, as a result of the n-type material used

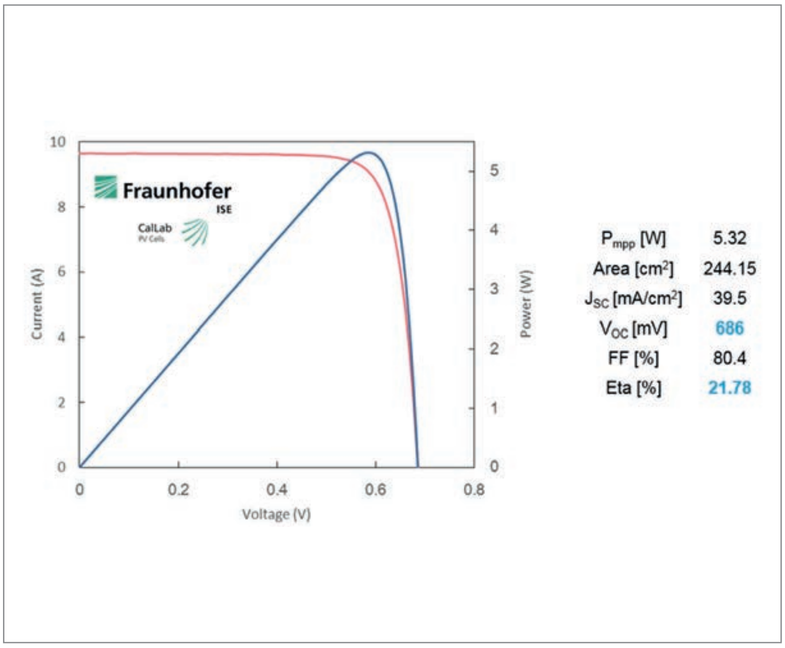
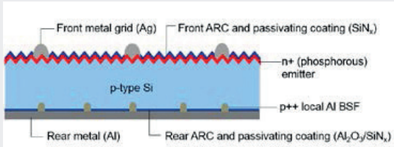


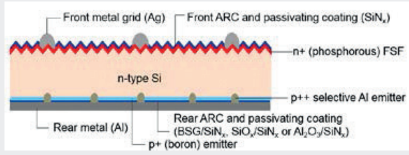
Figure 8. *I–V* measurement of a five-busbar MoSoN solar cell, certified by FhG ISE CalLab [15].

	FF [%]	V_{oc} [mV]	J_{sc} [mA/cm^2]	η [%]
$MoSoN_{best}$	80.1	693	40.0	22.2
$MoSoN_{bifi}$	79.4	692	40.0	22.0

Table 1. Latest MoSoN results for best mono- and bifacial devices with optimized point contacts.

as well as the totally diffused surfaces; moreover, these two factors guarantee not only high but also stable efficiencies. In the MoSoN process the AlO_x passivation tool can be replaced by a highly productive LP-BBr3 diffusion furnace from





	PERC	MoSoN
Technology	P-type front junction Selective emitter	N-type rear junction Homogeneous FSF
Efficiency in production	21.5–22% 22–22.5% (potential)	22% 22.5–23% (potential)
	<680mV	>690mV
Wafer	Low resistivity wafers required	Wide range of resistivities possible
Ag use	100%	90% (10% front-side Ag reduction)
Bifaciality	70–80%	75–85% (rear junction)
Degradation	Up to 20% in 3 years' LeTID (possible)	Not yet observed
Different machines	AlO_x passivation	BBr_3 diffusion (with BSG passivation)
COO cell	US¢16.4/Wp	US¢16.7/Wp*
Solar cell transformation costs (excl. wafer costs)	US¢8.3/Wp	US¢8.0/Wp
LCOE	US¢4.84/kWh** US¢4.21/kWh*** US¢4.05.0/kWh****	US¢4.57/kWh** US¢4.06/kWh*** US¢3.91/kWh****

** September 2018; ** Fixed-tilt monofacial; *** Fixed-tilt bifacial; **** HSAT bifacial*

Table 2. Comparison of standard PERC and MoSoN.

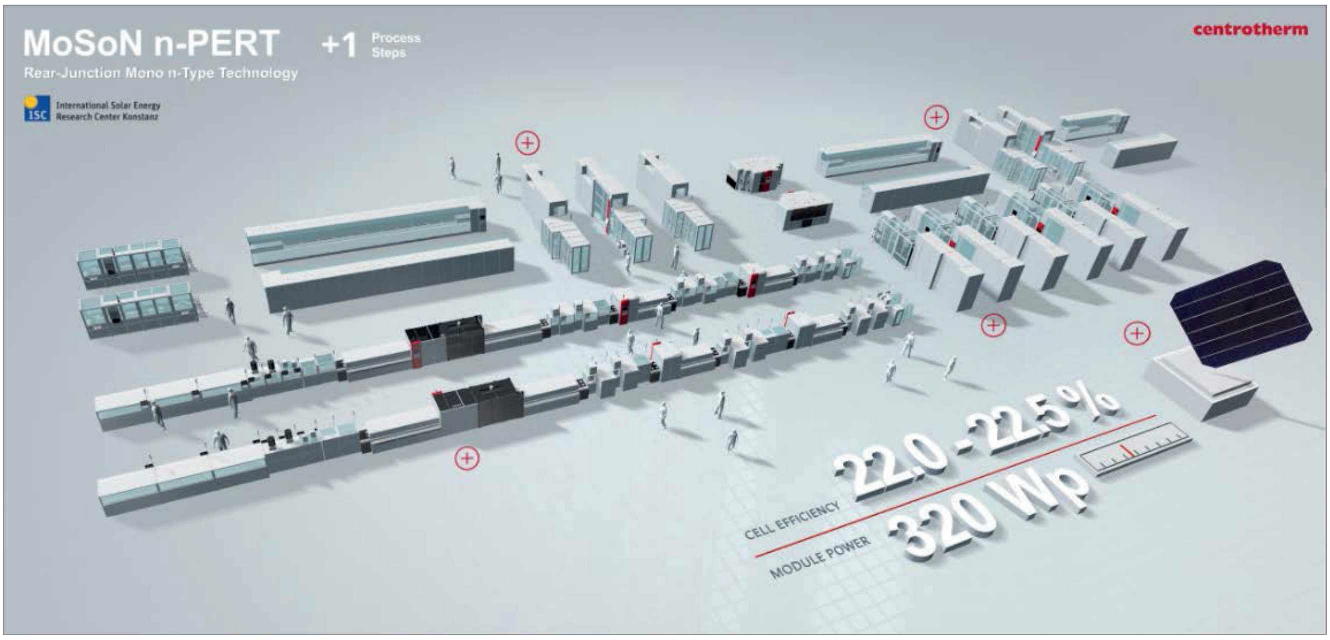


Figure 9. Lay-out of a possible MoSoN production line from centrotherm (from SNEC 2017).

centrotherm, which provides diffusion of the rear emitter and in situ passivation with good homogeneity [17]. Another advantage of this cell architecture is that the bulk conductivity of the wafer contributes to the lateral conductivity in parallel to the FSF. As a result, the rear-junction nPERT concept requires fewer Ag fingers than a PERC cell, thus saving Ag costs [18].

Fig. 9 shows a MoSoN production line proposed by ISC Konstanz and centrotherm. The COO will be discussed in the next paragraph, and a summary is presented in Table 2. Because the wafer price of n-type is still higher than n-type, the MoSoN cell is slightly more expensive. Nevertheless, the higher cost of a MoSoN module in a system environment is already offset by the advantages of higher efficiency, better stability and slightly higher bifaciality. For bifacial horizontal single-axis tracking (HSAT) MoSoN systems, a levelized cost of electricity (LCOE) of US¢3.9/kWh can be achieved

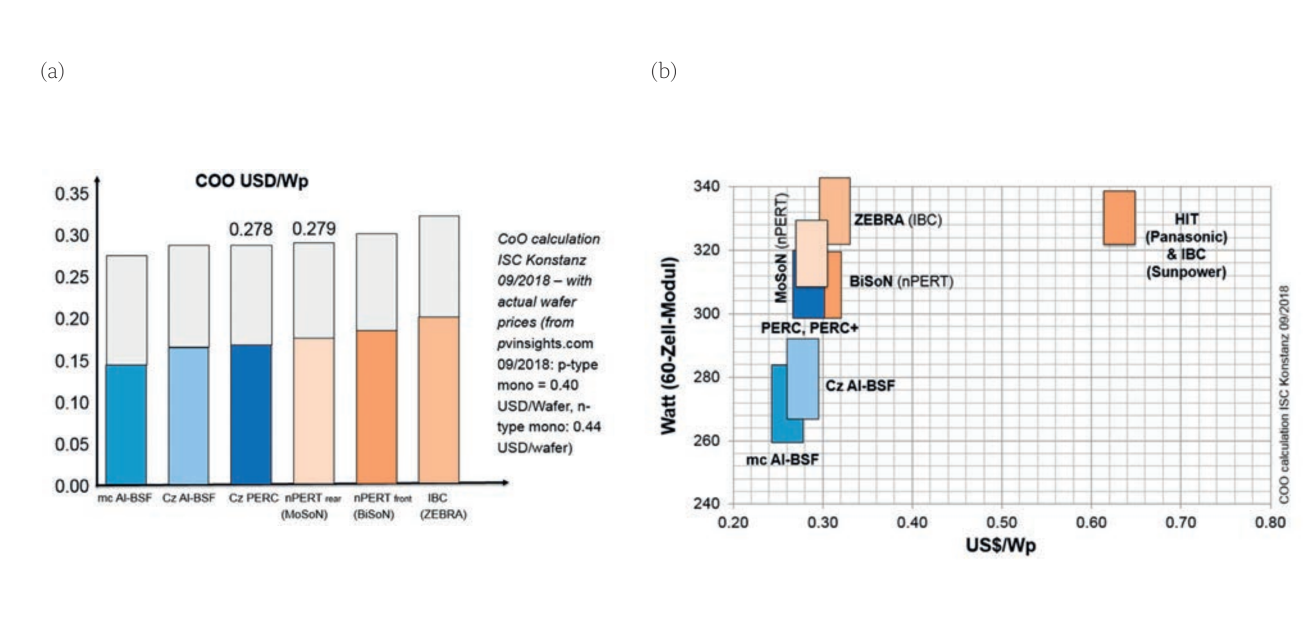


Figure 10. COO for different solar cell concepts: (a) broken down into solar cell and module costs; (b) as a function of the module power of a 60-cell module.

in locations with 1,875kWh/kWp/year irradiation and an albedo of 35% (typical for desert sand).

"The higher cost of a MoSoN module in a system environment is already offset by the advantages of higher efficiency, better stability and slightly higher bifaciality."

COO for PERC and PERT solar cells

N-type solar cells do not have to be expensive when the processes are based on standard p-type processes. Fig. 10 depicts the COO for standard solar cell products on the PV market. Since wafer price is very dynamic and still represents a large portion of a solar cell cost, the differences between processes are very dependent on the current wafer market. It is clearly visible, however, that current advanced solar cell processes, compared with those in the past, are getting very close to producing the lowest-cost mc-Si module. At the system level, it is nowadays important to select high-power modules in order to minimize the LCOE.

Since the MoSoN COO is low and the achievable module power high and stable, the authors considered it the best concept to go with.

Summary and outlook

After the long-term market monopoly of Al-BSF solar cells, PERC solar cells are becoming standard in solar cell production lines. This is good for PV, as higher efficiencies help to reduce the balance of system (BOS) cost of PV systems.

The authors believe that the next step following on from PERC is a switch to n-type material and rear-emitter standard nPERT concepts, because of the lower degradation potential and the higher efficiency potential, while keeping the process sequence simple. This next step does not yet include passivated contacts, since with a very cost-effective advanced Al paste technology, efficiencies of close to 23% and voltages of 700mV are also realizable in a simple way.

This paper has presented ISC Konstanz's rear-junction nPERT concept MoSoN, on n-type material from LONGi, achieving an efficiency of 22.2% and a high voltage of 693mV. This very low-cost advanced Al paste point-contact technology from Toyal offers the potential to achieve 23% using a simple process, with solar cell transformation costs of around US¢7/Wp (excluding wafers costs). This technology will, in addition, be used in the future to test and further develop ISC Konstanz's ZEBRA IBC solar cell concept, with the aim of reaching 24%.

Acknowledgements

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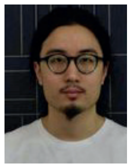
Dr. Radovan Kopecek obtained a Dipl. Phys. degree from the University of Stuttgart in 1998, and completed his Ph.D. dissertation in the field of c-Si thin-film silicon solar cells at the University of Konstanz in 2002. One of the founders of ISC Konstanz, Dr. Kopecek has been head of the advanced solar cells department since 2007; the department deals with several European and national research projects and technology transfers focusing on high-efficiency n-type devices and bifacial technology. Since 2016 he has been on the board of directors at EUREC – the European association for research centres involved in renewable R&D.



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Jan Lossen studied physics at the University of Freiburg, Freiburg im Breisgau, Germany, and at the University of Cologne, Germany. He graduated in 2003 with a thesis on the hot-wire chemical vapour deposition of microcrystalline silicon layers. For more than ten years he worked in different positions in the production and development of crystalline silicon solar cells with ErSol/Bosch Solar Energy AG. Since 2014 he has been a senior scientist and project manager for process transfers with ISC Konstanz.

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Dr. Wolfgang Jooss received his Ph.D. from the University of Konstanz in 2002 for his work on multicrystalline and rear-contact buried-contact solar cells; the major outcome of the experimental work was a world record 17.5% for a large-area multicrystalline solar cell. Between 2002 and 2009 he worked at sunways AG as an R&D engineer and became head of solar cell R&D. He joined centrotherm in 2009, where initially he was the director of integrated factory technologies, looking at the complete c-Si value chain, and subsequently the director of PV technology, responsible for the technology development of solar cell equipment. Since April 2016 he has been the director of R&D at RCT Solutions GmbH in Konstanz, Germany.

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