TOPCon technology: What exactly is it and how mature is it in production?

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Abstract

Over the last few years, passivated-contact nPERT solar cells, referred to as *TOPCon* cells, have been receiving increasing interest among solar cell manufacturers. At the beginning, the development was mostly initiated by n-type solar cell producers, but it is now also attracting the attention of many PERC producers, who are approaching the limits of their standard production lines. In this paper the situation of solar cell production in China is summarized, and an attempt is made to answer the question of whether passivated contacts could replace PERC technology, which will eventually reach its efficiency limit in the future. The most relevant passivated-contact technologies in R&D and production are reviewed, and the major bottlenecks impacting on a successful industrialization are evaluated. Some parallels are outlined between the situation today and the evolution from homogeneous Al-BSF technology to PERC in the past.

Introduction

Since 2016, when LONGi began introducing their low-cost Cz-Si wafers to the PV market, mc-Si and homogeneous Al-BSF technologies have been rapidly losing market share, as evidenced by Fig. 1. Back then, there was stiff competition between passivated emitter and rear cell (pPERC) and passivated emitter, rear totally diffused (nPERT) technologies, but PERC later prevailed – mostly because of the cheaper price of p-type wafers and associated processing sequences and materials (e.g. Ag and Al pastes). An additional advantage of PERC was the fact that the process sequence was closer to that for p-type standard cells, which facilitated a gradual adaptation of existing production lines.

PERC technology subsequently became, much more quickly than anyone expected, the leading solar cell technology, with the highest production capacity and the lowest cost of ownership (COO). Towards the end of 2019, mono PERC production capacity reached 95GWp (see Fig. 2), which corresponds to a total annual solar cell production of more than 120GW, equating to a 75% market share.

Standard PERC cell efficiencies, however, are expected to reach their limits soon; scientists in the PV community estimate that this will happen at an average production efficiency value of 22.5–23% [2]. Fig. 2 shows that, during the period Q2 2019 to Q3 2019, an increasing share of PERC production lines had been upgraded to produce cells with selective emitters, reaching a total of 75GW. This can be interpreted as an indication that PERC producers are approaching the efficiency limits of this cell technology, and are squeezing out the last efficiency gains from their production lines. To achieve even higher efficiencies with PERC-like solar cells, new technologies will need to be implemented.

This raises the question of which cell concepts will replace PERC as the leading solar cell technology of the future. Or, more specifically: how can the voltage of low-cost industrial solar cells be increased towards 700mV and beyond in order to obtain efficiencies well above 23%? And how can

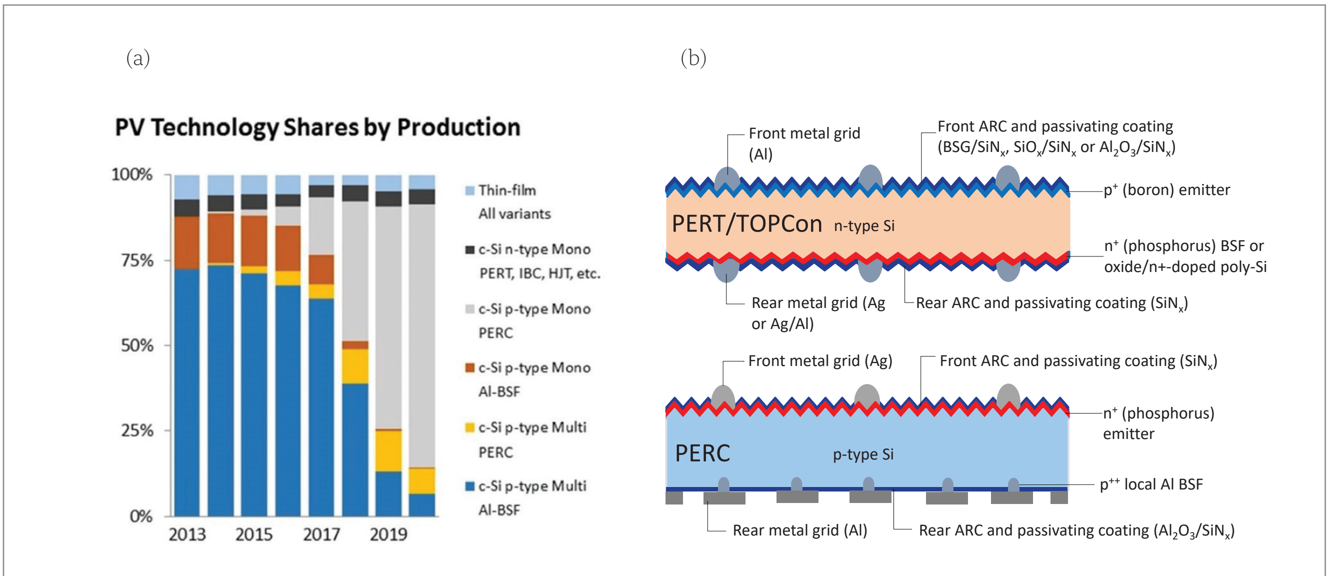

Figure 1. (a) Historical data and forecast for c-Si technology market share from PV ModuleTech [1]. (b) A typical cross section of an n-type PERT solar cell (top) and a p-type PERC solar cell (bottom).

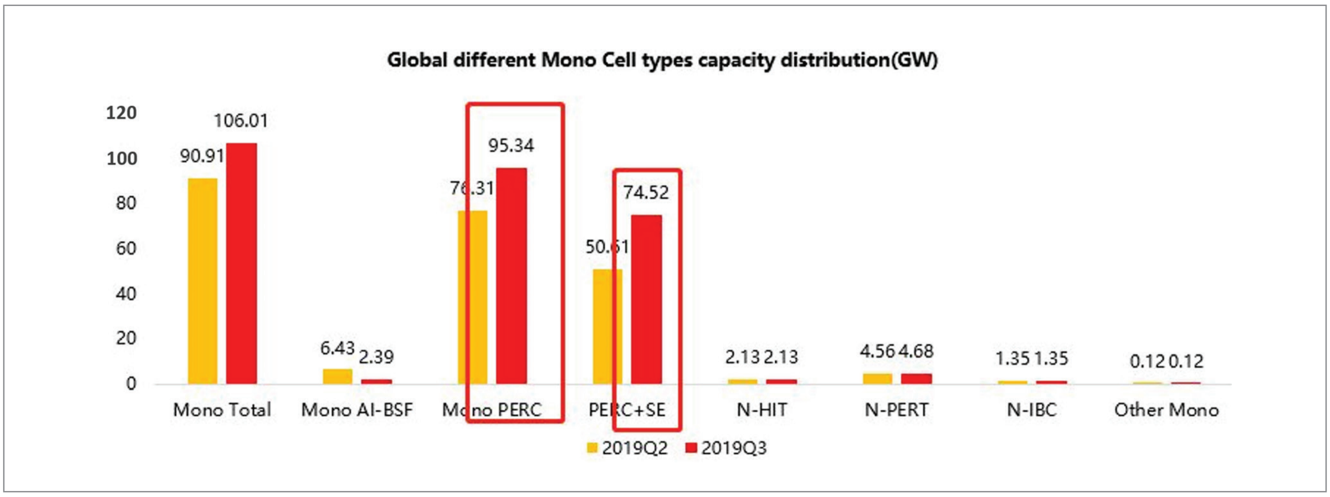

Figure 2. LONGi's data on Cz-Si solar cell technology market share in 2019. (PERC+SE are PERC structures that include selective emitters.)

this be achieved at acceptable costs, i.e. without the addition of too many and too costly new process steps? Fig. 3 shows that cell technologies with passivated contacts ('TOPCon' cells) can achieve the efficiency goal, but at a cost that is currently not competitive with that of PERC.

In 2019 many large PERC manufacturers, such as JinkoSolar and LONGi, reported at important Chinese PV conferences (e.g. PVSEC in Xi'an, SNEC in Shanghai or CSPV in Shanghai) that it is becoming increasingly difficult to maintain steady efficiency gains with standard PERC technology. As contact recombination is a main limiting factor, they concluded that passivated contacts would need to be implemented as a next step.

Solar cells with passivated contacts, in Asia often referred to as *TOPCon*, a term coined by FhG ISE for their passivated-contact solar cell, have been developed for both p-type and n-type cell concepts. The essential novelty with respect to conventional cell technologies is that diffused or alloyed regions of the cell are replaced by a stack of silicon dioxide and doped polysilicon (poly-Si). The replacement of n-doped regions by oxide/poly-Si stacks with excellent surface passivation was already achieved several years ago; for p-doped poly-Si layers, however, the process is more challenging [4]. Furthermore, it has to be taken into account that poly-Si layers are optically highly absorptive, making full-area application on the front side unattractive.

Most research institutes and cell manufacturers are therefore developing n-type cell concepts with poly-Si passivated contacts on the rear side, in particular nPERT (Trina Solar, Jolywood, JinkoSolar, SPIC and others) or n-interdigitated back contact (nIBC) cells (Trina, LG electronics) structures. Nevertheless, concepts for cell architectures based on p-type substrates – often called *polyPERC* – also exist [5]. Another alternative is p-interdigitated back-contact (pIBC) solar cells, combining n-poly layers with alloyed local Al contacts [6,7]; however, such a rear-junction cell concept suffers from the limited charge-carrier diffusion length of currently available commercial p-type Cz-Si substrates.

At the 29th International PVSEC in 2019 in Xi'an, an overview of the highest efficiencies obtained for large solar cells in China was presented and is shown in Fig. 4 [8]. An efficiency of 24.58% was achieved with a TOPCon nPERT cell by Trina, and 24.03% with a PERC-type cell from LONGi. While both the cells in question are assumed to use an intricately patterned poly layer on the front side (which is not suitable for cost-effective industrial production), the reduced charge-carrier recombination of the TOPCon rear side, compared with a standard PERC rear side, is clearly visible from the measured high V_{oc} of the TOPCon cells.

At the beginning of 2020, only a few companies had started pilot production or full production of TOPCon cells: examples are Trina, Jolywood, Linyang, JinkoSolar and SPIC. All of them use low-pressure chemical vapour deposition (LPCVD) of the poly-Si layer, a choice that is motivated by the excellent passivation quality of LPCVD-deposited poly-Si layers, as well as by the availability of corresponding deposition tools. However, it is the authors' understanding that significant challenges still remain, including the complex process sequence as a consequence of the conformal poly-Si deposition in the LPCVD process, and the necessity to deposit thick poly-Si layers for achieving sufficient passivation in combination with screen-printed firing-through metallization. The latter procedure further reduces the service life of the quartz tubes, one of the drawbacks of LPCVD deposition of poly-Si, which will be discussed in more detail below. These challenges will need to be overcome in order for TOPCon to compete with PERC, which requires not only achieving high efficiencies but also fulfilling the specifications in terms of throughput and yield. Typical specifications associated with these quantities for n-type solar cell production are shown in Table 1.

For a classical diffused nPERT cell, an efficiency of 23% was unattainable. Therefore, all nPERT producers have switched (or are currently switching) to TOPCon, where 23% *is* possible,

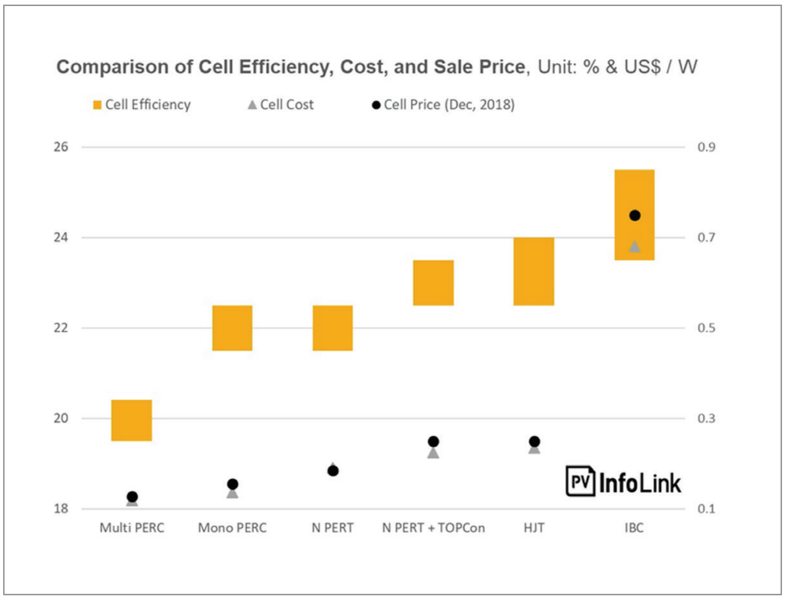

Figure 3. Efficiencies, COOs and selling prices for major c-Si technologies on the PV market [3].

although significant progress will still need to be made in order to fulfil the remaining specifications shown in Table 1. The costs for TOPCon cells must not be more than 1.2 times the costs for PERC, which is not yet the case, mainly because of the conformal deposition of poly-Si in the LPCVD reactors, leading to more complex processes, a lower yield and the short service life of the LPCVD quartz tubes (as well as because of the front and rear Ag metallization).

Consequently, alternative inline processes – such as atmospheric pressure chemical vapour deposition (APCVD), plasma-enhanced chemical vapour deposition (PECVD) and physical vapour deposition (PVD) – have been developed, which allow single-sided deposition of poly-Si. Furthermore, such alternative technologies allow the etching of residual poly-Si deposition from transport belts, holders or carriers, either continuously during the process or entirely outside of the reactor. These techniques will be discussed further later on. ISC Konstanz is evaluating many of these techniques in order to develop a simple and high-throughput process that can be transferred to the market in the coming years.

Achieving higher voltages as in PERC

A simple way of comparing different c-Si cell technologies is to look at their maximum voltages instead of efficiencies. The open-circuit voltage V_{oc} is a reliable measure of the recombination at high carrier concentrations, and defines the upper limits for both fill factor and cell power. A comparison of the measured efficiency, on the other hand, is sometimes misleading, as several institutes

"Standard PERC cell efficiencies are expected to reach their limits soon."

Cell concept	FF [%]	Jsc [mA/cm²]	Voc [mV]	Eta [%]
bifacial TOPCon TRINA	84.52	40.57	716.8	**24.58**
PERC LONGi	83.26	41.58	694.0	**24.03**

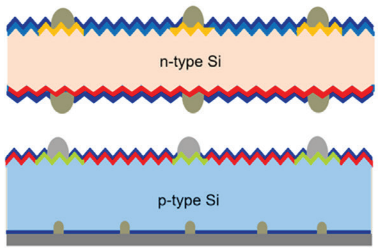

Figure 4. Highest efficiencies, measured at ISFH, for large-area PERT ('TOPCon') and PERC solar cells in China in 2019.

Efficiency [%]	>23
Throughput [wafers/sec]	~1.3
Capacity [MW/line]	>200
Yield [%]	>98
Cost of cell (relative to PERC)	<1.2
CAPEX (relative to PERC)	<1.3
Size	M4, M6

Table 1. Current manufacturing specification requirements for n-type cells [9].

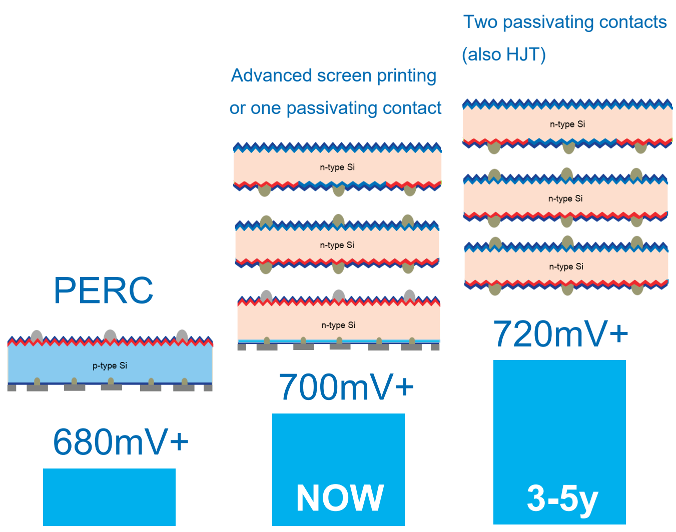

Figure 5. Classification of solar cell technologies in terms of V_{oc}.

"The costs for TOPCon cells must not be more than 1.2 times the costs for PERC."

and companies report results from busbar-less measurements, or they report active-area efficiencies by subtracting the shading of the front-side metallization. Fig. 5 shows the three categories with V_{oc} ranges that can be achieved using low-cost solar cell processes today and that could be achieved in the future.

Typical voltages for PERC solar cells are around 680mV, with slight increases being possible when using selective emitter technologies. A voltage of around 700mV can be reached when applying passivated contacts to one polarity of the cell – for example by replacing a diffused rear side with a silicon oxide poly-Si stack. The latter is much easier for n-type technologies, since in this case the $PCOl_3$ diffusion is on the rear side. Instead of using passivated-contact technology, a reduction of the metallized surface area, for example by the use of point contacts, enables the voltage of the cell to be increased. With a flat boron-diffused surface (rear emitter PERT or IBC), it is possible to obtain voltages of the order of 700mV. Such high voltages without passivated contacts have been achieved by imec in collaboration with Jolywood with their rear emitter nPERT [10], by ISC Konstanz with MoSoN cell technology [11,12], and by ISC in collaboration with SPIC with ZEBRA technology [13].

In order to reach 720mV, passivated-contact technology is required for *both* polarities – as also employed for heterojunction (HJT) cells. However, as of now, the equipment for such processes is very expensive, so typical manufacturing specification demands cannot be fulfilled yet. To reach even higher efficiencies, new devices – such as four-terminal tandem technologies with c-Si bottom solar cells and Perovskite solar cells on top – could be the answer within the next five to ten years.

'TOPCon' (passivated-contact technology) – what is it exactly?

Poly-Si passivated carrier selective contacts employ a thin silicon oxide layer to separate a highly doped poly-Si layer from the bulk absorber of the solar cell, as shown schematically in Fig. 6. This structure allows a high majority-carrier current towards the metal electrode contacting the poly-Si layer. The minority-carrier current, in contrast, is effectively blocked at the interface oxide, which suppresses interface state-mediated charge-carrier recombination at the metal contact.

The basic idea of using the passivated-contact concept (which is well known in bipolar transistor technology) for solar cells dates back to the 1980s. However, it did not receive much attention at that

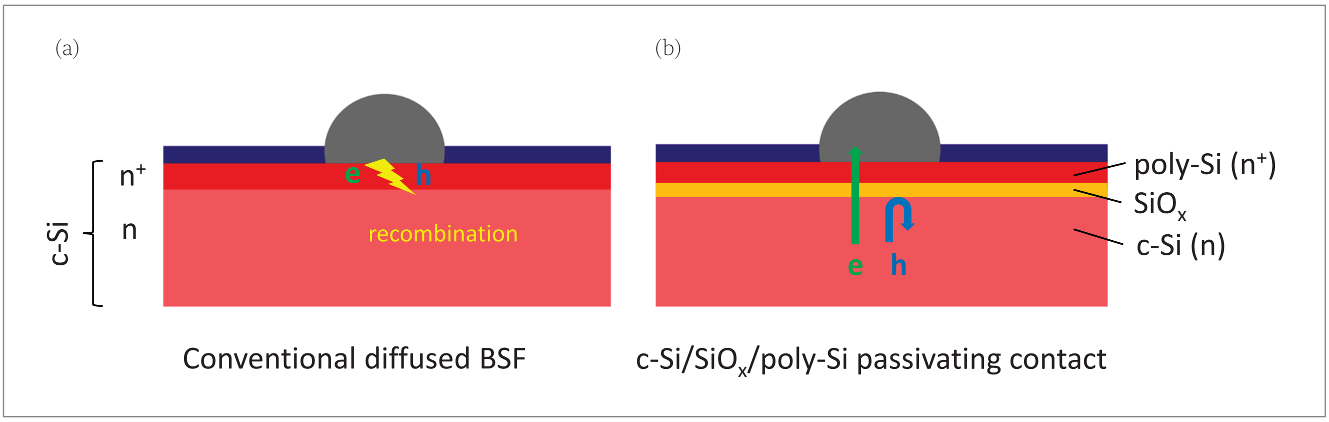

Figure 6. Schematic cross sections (not to scale) of: (a) a conventional diffused back-surface field (BSF); (b) a layer stack for a poly-Si passivated contact.

Efficiency	Cell type	Research institute/company
25.2%	Tunnel layer passivated IBC solar cell	SunPower
25.7%	Front- and rear-contacted TOPCon solar cell	FhG ISE
26.1%	Poly-Si on oxide (POLO) passivated-contact IBC solar cell	ISFH

Table 2. Highest efficiencies achieved using the different technologies.

PERC 2010	Substrate mc-Si Cz-Si Low O LID	Passivation AlO_x Thermal SiO_2 SiC_x	AlO_x Spatial ALD Batch ALD, Remote PECVD Plate PECVD	Metallization Evaporated Screen printed LFC Laser opening Chemical opening	Other Cell structure Process flow Stabilization PID Bifacial Yield Cost
TOPCon 2018	Substrate p-type n-type	Thin oxide wet chemical UV Thermal	Poly-Si LPCVD PECVD APCVD Sputter PVD HWCVD EB PVD	Metallization Evaporation Screen printing TCO Plating Al paste	Other Cell structure Process flow UV degradation PID Bifacial Yield Cost

ALD = atomic layer deposition; LFC = laser-fired contact; LID = light-induced degradation; PID = potential-induced degradation; HWCVD = hot-wire chemical vapour deposition; EB PVD = electron beam physical vapour deposition; TCO = transparent conductive oxide

Table 3. Open questions during PERC development starting in 2010, and during TOPCon development from 2018 onwards (adapted from Chen [17]).

time, as silicon solar cell efficiency was still more severely limited by other components of the device. It is believed that SunPower was the first company to commercially use passivated-contact technology to increase the efficiency of their IBC cell, but the company never disclosed any details on the cell architecture.

Passivated contacts for solar cells have been receiving ever-increasing attention since 2014, when the group of Prof. Stefan W. Glunz at Fraunhofer ISE researched the fundamental properties of the passivation layer stack using modern characterization methods [14]. Fraunhofer ISE also coined the name *TOPCon* as the abbreviation for 'tunnel oxide passivated contact' – initially for a PECVD-deposited Si-layer stack with carbon admixture, but eventually for all kinds of poly-Si layer on a SiO barrier layer. Other research institutes picked up the topic and contributed valuable insights in areas such as transport through the oxide (ISFH), the influence of doping profile variations (ECN), and alternative deposition methods (ANU, SERIS, ISC, FZJ). Record efficiencies for small-area laboratory cells were achieved by Fraunhofer ISE with 25.7% [15] for two-sided solar cells, and 26.1% for an IBC by ISFH [16] (see Table 2).

How mature are passivated-contact technologies in production?

Solar cell architectures which employ passivated contacts (TOPCon) and are produced by different manufacturers today are very similar, even though

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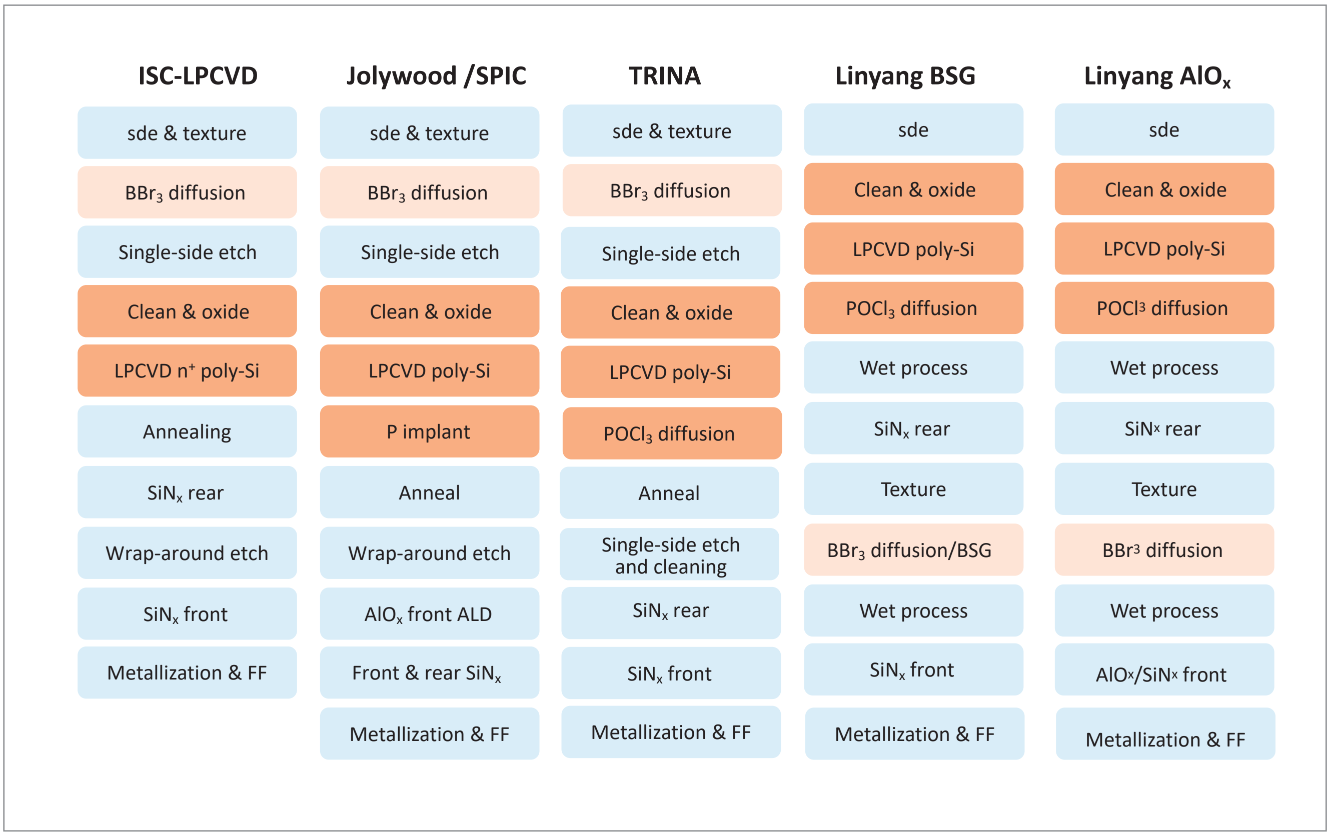

Figure 7. Different process flows for nPERT cells with a rear-side passivated contact.

Company	Capacity [MW]
Jolywood	2,200
Yingli	800
JinkoSolar	800
LG	500
Linyang	500
Trina	500
SPIC	400
Total	**5,700**

Table 4. Companies with passivated-contact nPERT capacity in 2019 [9].

Boron diffusion	Poly-Si LPCVD
Centrotherm	Tempress
Tempress	Semco
Semco	Centrotherm
Laplace	Laplace
7-Star	Polar
P&Tech	P&Tech

Table 5. Two key steps for TOPCon and selected equipment suppliers [9].

the processing sequences may differ. Table 3 depicts a collection of different technology options that companies have been able to choose from during PERC development since 2010, and now during TOPCon development since about 2018 [17]. These choices had to be (and still have to be today) carefully evaluated by considering the associated cell efficiency potential and the matureness and cost of the process. Diffusions of the front side are carried out by quartz tube diffusion, in a $POCl_3$ atmosphere for PERC and in a BBr_3 atmosphere for TOPCon. Other processes had to be (and still have to be) evaluated too – such as the selection of substrate, passivation layers, stabilization treatments, and opening of dielectrics, as well as metallization technology and respective pastes.

For passivated-contact nPERT technology, the most critical process is the formation of the poly-Si layer. Here the question remains how to achieve a sufficiently doped one-sided poly-Si layer so as to keep the process simple and cost effective. However, the metallization remains challenging too, as lower-temperature Ag pastes need to develop in order to achieve a good contact without penetrating the thin oxide layer. The company Toyal is even suggesting the use of low-temperature Al pastes to make this process more cost effective.

Even though these challenges have not yet been completely surmounted, several companies are already moving towards production; see Table 4 for a summary. Jolywood has the highest production capacity; however, this relies on fairly complex ex situ doping of the LPCVD poly-Si layers by ion implantation. The total capacity of all passivated-contact nPERT producers is about 6GW, of which a total of 4GW is accounted for in 2019.

As already discussed, the COO falls short of being competitive with PERC, as all the process flows involved are still too complex. Fig. 7 shows several process flows published by the major TOPCon producers, along with ISC Konstanz's LPCVD reference process.

What the different processes have in common is that the $POCl_3$ diffusion is replaced by the formation of a thin interface oxide and a subsequent LPCVD poly-Si deposition. The resulting silicon thin film is then doped ex situ via $POCl_3$ diffusion (Trina, Linyang) or via ion implantation (Jolywood and SPIC). As illustrated by ISC Konstanz's process flow, the doping of the poly-Si layer can also be achieved via in situ doping during deposition, but at the expense of a reduced deposition rate.

A significant difference between the process flows of Linyang and the other companies is the sequential arrangement of the emitter diffusion and the poly-Si deposition. Whereas Linyang uses a process flow in which the BBr_3-diffusion is performed after the LPCVD deposition of poly-Si, the other published processes implement the poly-Si deposition after the BBr_3 diffusion. Both approaches have different advantages and challenges concerning the front- and rear-side passivation.

Emitter passivation can be achieved using either a stack of AlO_x/SiN_x or a combination of boron silicate glass (BSG) and SiN_x, as exemplified by the two different Linyang process routes. Even though record efficiencies of above 24% can be realized by an adapted TOPCon process, average efficiencies in production vary between 22.8% (SPIC/V_{oc} = 695mV) and 23.3% (Linyang with AlO_x/V_{oc} = 695mV). Jolywood's average efficiency in production is reported to be 23.1% with a V_{oc} of 700mV, while Trina has published an average efficiency of 23.0% with an average V_{oc} of 702mV [18]. The record TOPCon efficiency from Trina of 24.58% with a voltage of 717mV is suspected to have been achieved using a selective passivated contact on the front as well, similarly to the record 'PERC' cells from LONGi. A very good summary for all high-efficiency solar cell technologies on the market is also given in the report from Tayiang News [19].

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In order to obtain not only high efficiencies but also low COO, several bottlenecks of the TOPCon process routes described above need to be addressed. One of the most important questions concerns the technology for poly-Si deposition, as detailed in the following section.

Comparison of poly-Si deposition technologies

As of now, most cell manufacturers are focusing on developing passivated contacts using LPCVD deposition of poly-Si (Table 5). This choice is motivated by both the excellent passivation quality achieved with these layers, and the availability of industrial-scale deposition tools developed for the deposition of poly-Si in the semiconductor chip industry. While the results based on LPCVD deposition of poly-Si published by various cell manufacturers and research institutes are promising, this technology presents several challenges.

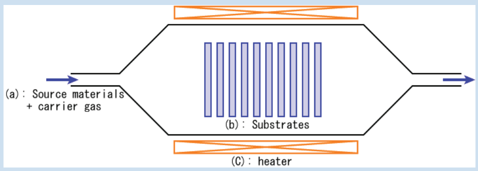
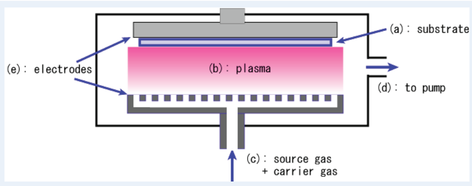
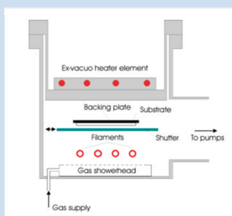
Deposition technique	Features	Schematic
LPCVD	- Hot wall CVD - No ion impact needed - Very conformal deposition BUT: both sided and tubes cracking	
PECVD	-Single-sided deposition -Lower temperature than LPCVD BUT: wrap around	
HWCVD	- Much higher deposition rate than PECVD -Single sided BUT: machine not industrial	

Figure 8. A selection of process technologies for the creation of poly-Si layers for passivated-contact technology.

An inherent disadvantage with many cell concepts is the conformal deposition of the layer, which requires dedicated process steps for single-side etching of poly-Si. Moreover, the lifetime of the quartz tubes is usually limited to a total deposition of around 100μm of poly-Si, owing to the increasing internal stress, which eventually leads to tube breakage. Since typical poly-Si layer thicknesses of 150–300nm are currently required for sufficient passivation after metallization [20,21], the quartz tubes must be replaced after ~700 runs.

In addition, the wafer throughput is limited by the deposition rate of around 3–6nm/min, which is further reduced when adding phosphine for in situ phosphorus doping of the layer. The latter issue can be mitigated by employing ex situ doping, e.g. using $POCl_3$ diffusion after the poly-Si deposition.

Given the challenges concerning the conformal deposition and the throughput of the LPCVD process, several alternative technologies have been investigated by research institutes around the world (Fig. 8). Possible single-sided deposition methods for poly-Si include different chemical vapour deposition processes (PECVD, HWCVD and APCVD), and various physical vapour deposition (PVD) processes, e.g. sputtering of silicon. Industrial tools are available for all of these processes, but not necessarily for the specific application of depositing highly doped and ultrapure silicon thin films. Research on optimizing these alternative processes for the production of solar cells with passivated contacts is therefore currently gaining increasing attention.

Silicon layers deposited via PECVD have been successfully integrated into TOPCon nPERT cells, leading to efficiencies of around 23% [22]. One of the main challenges of the PECVD-deposited silicon layer is the incorporation of hydrogen, which can lead to blistering of the layer. To avoid such effects, the deposition conditions – in particular temperature, gas flows, pressure and plasma power – need to be carefully optimized, making the optimization of the process more challenging than LPCVD depositions. Additionally, the wrap-around has to be minimized by dedicated carrier designs.

HWCVD deposition of the silicon layer uses hot wires to dissociate precursor gases. As with PECVD, in situ doping of the layers can be achieved, for example using phosphine and diborane as the dopant source. One of the key advantages of HWCVD is the potential to deposit a poly-Si layer with excellent surface passivation at very high deposition rates of up to 42nm/min [23].

Finally, PVD technologies, such as sputtering of silicon, can also be used as an alternative. In situ boron-doped layers have been successfully integrated into p-type TOPCon cells with sputtered poly-Si and full-area metallization on the rear side, achieving 23% efficiency [24]. Excellent surface passivation has also been demonstrated for ex situ phosphorus-doped layers produced by sputtering of intrinsic silicon [25]. Sputtering of silicon could be an attractive alternative, offering a high-throughput process that produces a hydrogen-free silicon layer, without the need for any toxic gases and hence avoiding blistering of the layers.

“Solar cells with passivated contacts, and other high-voltage devices with high bifaciality factors, will become important in the future in order to achieve 1US¢/kWh in HSAT bifacial systems.”

Summary and outlook

Passivated-contact technology implemented in nPERT structures, often referred to as *TOPCon* in China, is likely to be the next step after PERC technology, which is slowly approaching its limits. The total production capacity of TOPCon in 2019 was 5.7GW. However, there are still many challenges remaining to make this promising technology cost effective and competitive with PERC. The process needs to be simplified, mainly by developing high-throughput processes for single-sided deposition of poly-Si with in situ doping. Some progress in silver paste composition also has to be made in order to further reduce the poly-Si layer thickness while maintaining excellent passivation after metallization. On top of that, replacing Ag metallization either partly or fully by Al metallization, without cannibalizing cell performance, as suggested (for example) by Toyal, would lead to a further essential cost reduction.

PV technologies nowadays are moving towards higher front-side power and higher bifaciality, in order to save balance of system (BOS) costs in utility-scale systems. Since a higher voltage results in a lower temperature coefficient, solar cells with passivated contacts, and other high-voltage devices with high bifaciality factors, will become important in the future in order to achieve 1US¢/kWh in horizontal single-axis tracking (HSAT) bifacial systems. Such a low levelized cost of electricity will allow PV to enter the sustainable TW era in the coming years.

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About the Authors

Dr. Radovan Kopecek obtained his Diploma in physics at the University of Stuttgart in 1998. He also studied at Portland State University (Oregon, USA) and obtained a master's there in 1995. He finalized his Ph.D. dissertation in Konstanz in 2002, and was a group leader at the University of Konstanz until the end of 2006. Dr. Kopecek is a co-founder of ISC Konstanz, where he has been working as a full-time manager and researcher since 2007, and is currently the head of the Advanced Solar Cells department. He has also been on the board of directors of EUREC since 2016.

Dr. Jan Hoß studied physics at the Karlsruhe Institute of Technology (KIT), Germany. He received his Ph.D. in 2017 from ETH Zurich, Switzerland, where he contributed to the development of a semiconductor detector for high-energy particles for the Compact Muon Solenoid (CMS) experiment at CERN's Large Hadron Collider. In 2017 Dr. Hoß joined ISC Konstanz as a research associate, where he is involved in developing n-type solar cells with charge-carrier selective contacts, with a major focus on alternative poly-Si deposition technologies.

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

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