TAIYANGNEWS

ALL ABOUT SOLAR POWER

TOPCon Solar Technology

2021 Edition

Increasing Interest In PERCs Natural Successor

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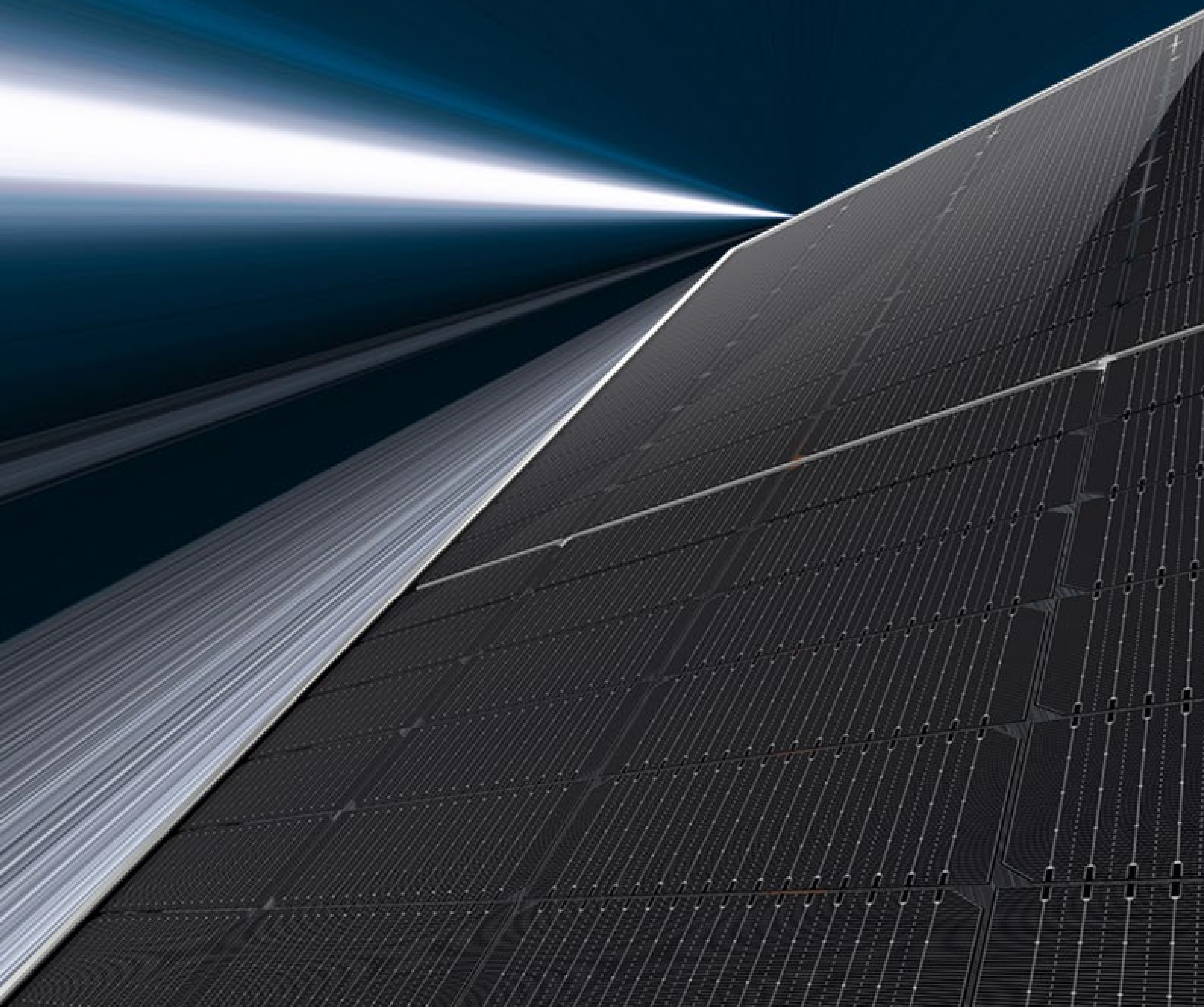
JinKO Solar

Tiger Neo · 620 W

N-Type TOPCon - A Notch Above



Executive Summary

There are several ways to improve the efficiency of a photovoltaic cell – and choosing the technology is a very important one. Such a technology that has found renewed interest of late is TOPCon. This was evidenced by the number of TOPCon module products presented at the world's largest solar show, SNEC 2021 in June. And in the meantime, several new TOPCon cell efficiency records have been broken.

Our research shows that the leading TOPCon manufacturers are in of an efficiency race in the production environment. While TaiyangNews has covered TOPCon as part of the high efficiency cell technologies report published 2 years ago, this newfound attention towards TOPCon was motivation enough for us to do a deep-dive on the technology.

At the heart of the technology lies passivating the contacts to reduce the recombination in the metallization area. In theory, the cell is applied with a thin silicon oxide topped with polycrystalline silicon, which is doped subsequently. The common industrial practice is to apply this structure on the rear side of the n-type cell.

Deposition technologies play a pivotal role in the TOPCon process. The early adopters initially followed in the footsteps of the semiconductor industry by using LPCVD for the deposition of polycrystalline silicon. This method, however, suffers from undesired deposition of polysilicon layer on the front, called wraparound, which must be removed actively. This not only increases cost with the increased number of steps involved but also leads to reduced yield. Given its propensity to innovate, the PV industry started using tweaked horizontal-loading LPCVD configurations to keep the wraparound within limits. We have also seen several other deposition technologies being developed in parallel. Today, almost every deposition technology known in PV, including PECVD, PVD and PEALD, has a tweaked version for application in TOPCon. These tools are designed to cover all facets of rear surface engineering — application of tunneling oxide, deposition of polysilicon and the subsequent doping. What's more, they are already capable of handling larger wafers of up to 210 mm (G12).

Besides the deposition of the structure itself, the TOPCon process involves some additional steps over PERC. One such process is emitter formation via boron diffusion. Annealing might be another additional step, depending on the polysilicon doping mechanism. Like PERC, TOPCon also requires emitter passivation, but the dielectrics used are inversed as the base substrates are of opposite polarity. The metallization process itself doesn't require any changes as such. The pastes, however, do require a certain degree of optimization to be processed at low temperature — the technology requires silver pastes on both sides. Plating would be an effective alternative to reduce the silver consumption to reduce costs.

TOPCon has the highest theoretical efficiency potential at 28.7%, while the highest lab efficiency of 26.1% has been reached by ISFH. JinkoSolar holds the latest record for an industrial processed cell at 25.4%, whereas several manufacturers have achieved average production efficiencies exceeding 24%. Different configurations of TOPCon modules are available from several companies, as shown in this report. As for the power rating, Jolywood is at the top with its 700 W module built with 66 of G12 size cells.

At the system level, the earlier TOPCon modules were mainly promoted for rooftops, a segment which attracts a price premium. Of late, though, with the shift to larger modules, the latest product ranges from leading suppliers are focused on utility-scale applications.

An important attribute that helps TOPCon to also address the power plant segment is the lower temperature coefficient (0.32%/°C) of this technology, which makes it suitable for regions with high irradiation, the prime location for large-scale utility solar. Moreover, TOPCon modules are immune to LID, and the performance lost due to LeTID is negligible, if any, as they are built on n-type base wafers. While the bifaciality of these modules is lower vis-à-vis its n-type peers, it is higher than today's incumbent, PERC.

Jolywood has been the pioneer in the field of commercial TOPCon cell/module production with the largest installed capacity of 2.1 GW at cells and 3 GW of modules and plans toward 20 GW (see interview, p. 46). But several companies have started larger scale pilot projects and are adding incremental capacities.

As things stand, the CapEx for TOPCon is about 20% higher than PERC. However, as TOPCon gains more traction and as the pool of vendors increases in size, along each deposition technology stream, capital expenditures are expected to reduce down the line. Double-side silver and n-type wafers being the two main contributors to operational costs of the technology, further optimization can lead to savings in this area as well.

Our first report on TOPCon provides an overview on the latest in technology research, equipment, cost, products, active players and their plans.

Enjoy reading our report on TOPCon Solar Technology – 2021 Edition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Propelling the transformation

25.21%
N-type TOPCon Solar Cell Efficiency

25.19%
P-type TOPCon Solar Cell Efficiency

26.30%
HJT Solar Cell Efficiency

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TAIYANGNEWS ALL ABOUT SOLAR POWER

TOPCon Solar Technology Report 2021
ISBN 978-3-949046-08-7

Publisher:
TaiyangNews UG (haftungsbeschraenkt)
An der Golzheimer Heide 23
40468 Duesseldorf, Germany
www.taiyangnews.info

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Niwa Super

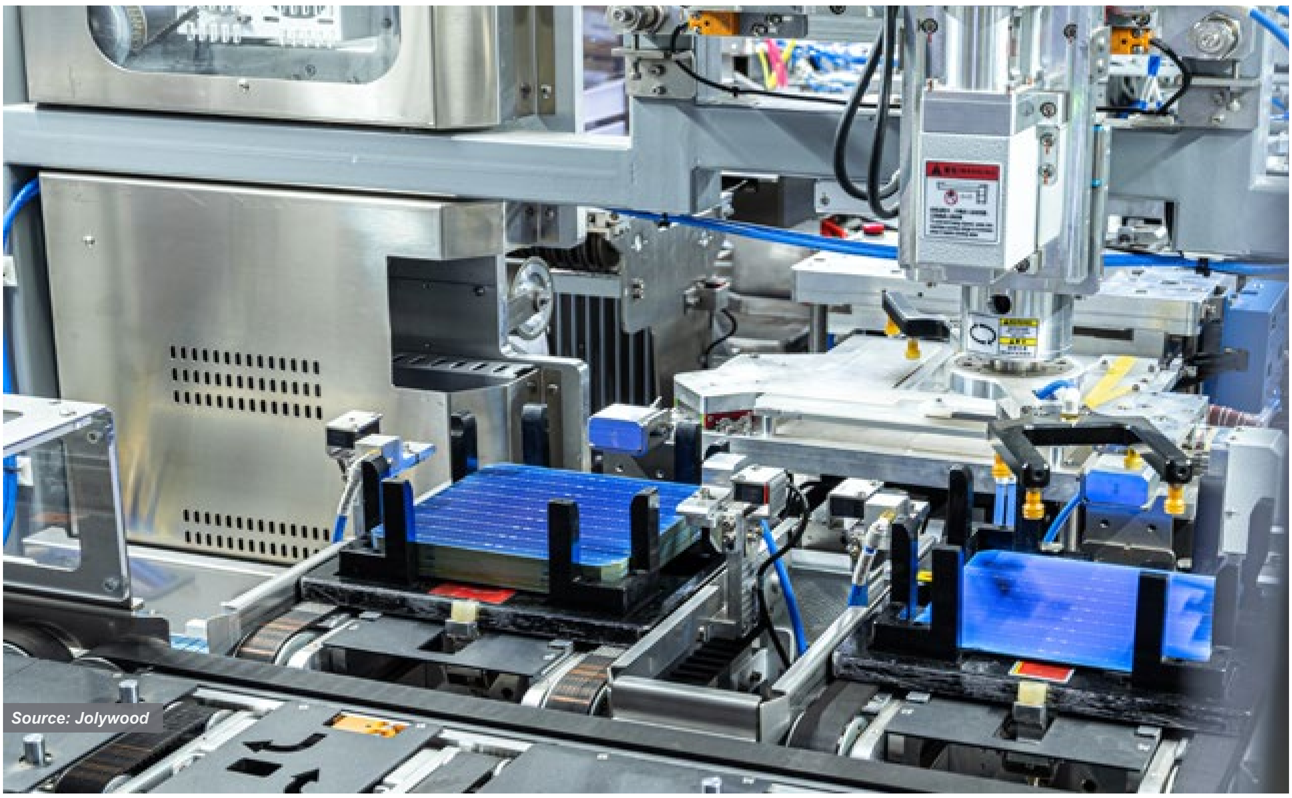
Power Output	Module Efficiency
615W	**22.00%**

- 10-30% Additional Power Generation Gain
- ZERO LID (Light Induced Degradation)
- Lower LCOE
- Better Weak Illumination Response
- Better Temperature Coefficient
- Wider Applicability

1. Introduction

While mostly a 'Chinese' show due to Corona-related travel restrictions, SNEC 2021 in Shanghai was again an eye opener to its visitors and beyond. The show did throw up a few surprises - and probably the biggest of them all was the industry's interest in TOPCon. At the show, it became evident that not only the leading manufacturers, who had been working on this cell technology in their R&D silos, got a feeling for how much interest the technology has garnered apart from themselves. So much so that it even surprised us. For a little background, as we prepared our agenda for TaiyangNews Very High Power Modules virtual conference, which was also a preview event for SNEC 2021, we realized, albeit at a very small level, that the interest in TOPCon is increasing. With a slew of TOPCon based product launches at this world's largest PV trade show, the proof was in front of the world's eyes.

A brand name for Germany's Fraunhofer ISE's proprietary technology and a colloquial name for Passivated Contacts, we covered TOPCon as part of **TaiyangNews High Efficiency Cell Technologies 2019**. Since then, several developments have taken place in this area. Jolywood, leading the companies active in this field, has been producing TOPCon products in high volume manufacturing, while also working on improving the technology in parallel. At our event it present development of a new 2nd generation TOPCon technology. In addition to Jolywood, a few other companies have announced efficiency improvements for the technology, which has also attracted new equipment makers to offer production solutions for TOPCon. At SNEC 2021, several leading PV manufacturers, including LONGi Solar, JinkoSolar and JA Solar, introduced new TOPCon modules, as announced at TaiyangNews Very High Power Solar Modules Conference. In this first exclusive TaiyangNews TOPCon Solar Technology 2021 Report, we do a deep-dive on the recent developments associated with TOPCon production and the process.



Source: Jolywood

Topping the interest: Jolywood was the only company to commercially produce TOPCon products in GW scale until recently. Now, a few more companies have joined – maybe indicating the start of the long awaited true kick-off for the technology.

ASTRONERGY
A CHINT COMPANY
ASTRO 6 670W
ASTRO Series Module
Tier 1
Bloomberg
Underwritten by
International Insurer
DNV GL
2021 TOP
Performance
ctc
Green Building
Materials
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欢迎关注正泰新能源微信
Create Sustainable and Efficient Green Energy
SH: 601877

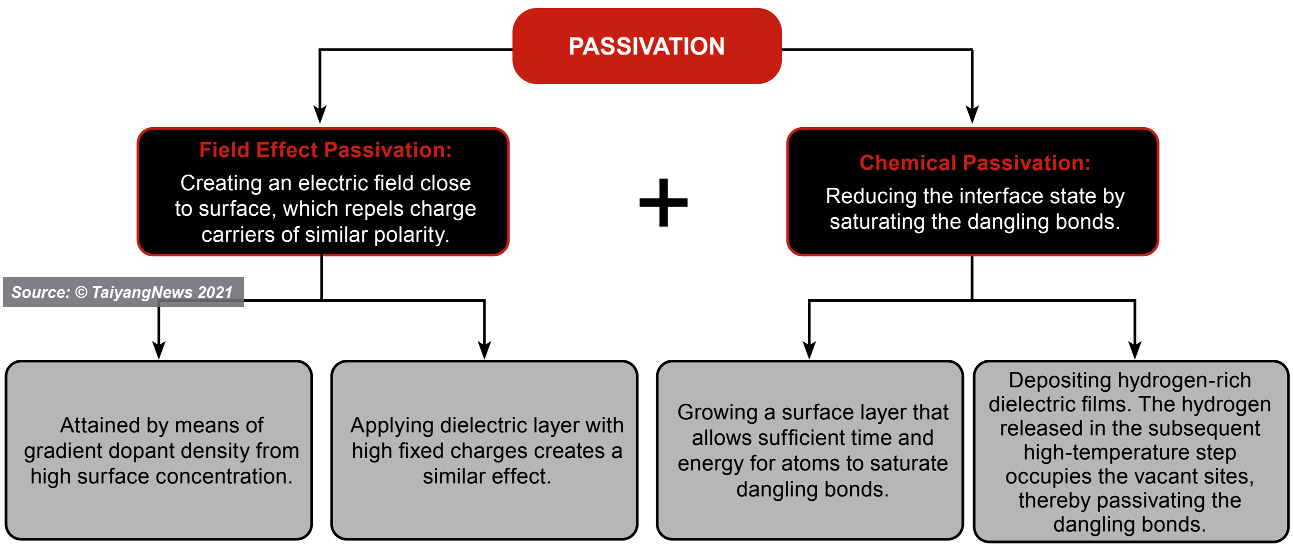
2. Basics of TOPCon

All advanced cell technologies have a different cell structure and follow a fairly different process flow. TOPCon involves a few additional process steps compared to standard PERC. Among the other advanced cell technologies, the IBC process is also promoted as an extension of PERC, while HJT follows a completely different manufacturing flow. However, from a broader perspective, the passivation scheme is the key differentiating element for all these high-efficiency cell technologies. Tweaking the metallization process according to the passivation configuration is another important part of implementing all these advanced cell technologies. The term 'passivated contacts', the generic name for TOPCon, itself indicates the significance of passivation properties of the technology. Before going into details of the technology, the following subsection summarizes the basics of passivation — also with regard to each of the advanced cell technologies.

2.1 Basics of Passivation

The silicon wafer — the basic raw material — still has inherent defects at the time of entering a cell line. Most prominent are surface defects originating from the fundamental process of slicing the wafers from an ingot causing disruptions of a crystal lattice at both wafer surfaces. These interruptions in the periodical arrangement of silicon atoms result in dangling bonds, working as recombination centers. Passivation is a process in which these defects are made inactive to reduce the surface recombination of charge carriers, safeguarding cell efficiency.

There are two complementing methods of passivation: a) strongly reducing charge carriers of one polarity reaching the surface, and b) reducing the interface state by saturating the dangling bonds. The latter can be accomplished, again, in two ways. One is to simply saturate the dangling bonds on the surface by providing suitable conditions to grow a surface layer that allows sufficient time and energy for atoms to reach optimal energy levels to saturate these dangling bonds. Alternatively, one can deposit a hydrogen-rich dielectric film that releases hydrogen in subsequent firing steps. The free hydrogen occupies vacant sites of dangling bonds, thereby pacifying them. This method is called **chemical passivation.** There exists another mechanism called **field effect passivation**, which involves creating an electric field close to the surface that can repel the charge carriers of similar polarity. It can be achieved by means of descending dopant density from high surface concentration. Alternatively, applying a dielectric layer with high fixed charges also creates an electric field gradient near the surface, which provides field effect passivation (see graph).



Passivation fundamentals: Passivating the silicon surface can be accomplished in two ways – chemical and field effects – and the methods are complementary too.

Following this basic principle, every advanced cell architecture features a specific passivation scheme.

PERC: The most prominent upgrade associated with PERC over the standard Back Surface Field (BSF) cell architecture, which has largely replaced the latter, also has to do with passivation. While aluminum provides a field effect passivation, PERC provides a chemical full-fledged passivation on the rear side of the standard cell by means of aluminum oxide. This dielectric, in addition to providing a good chemical passivation, also provides a field effect passivation with its high net positive charge.

n-PERx has two predominant cell architectures that are based on the n-type base wafer, namely PERT and PERL, both of which also bring superior passivation attributes to the table. PERT (Passivated Emitter, Rear Totally-diffused) involves a second diffusion step to form a phosphorus BSF. This approach provides an enhanced field effect passivation. The chemical passivation is then taken care of by the dielectric layers deposited on both the surfaces. **PERL** (Passivated Emitter Rear Locally-diffused) is another member of the PERx family. This structure combines the advantages of PERC and PERT. As with PERC, both the front and rear surfaces of the cell are passivated, but the rear is locally diffused only at the metal contacts.

Passivated contacts technology is an advanced cell architecture with true next level passivation. Apart from covering the surface passivation requirements, it is also aimed at addressing one main shortcoming associated with previously discussed cell structures. Metal contacts formed in most of these approaches are highly recombination-active and cause losses. This can be avoided by electronically separating contacts from the absorber by insertion of a wider bandgap layer. Passivated contacts by definition cover many technologies that are known by different names in the solar industry, including IBC and HJT.

However, the scope of the current report is limited to the structure using tunneling oxide that enables the majority charge carriers to pass and prevent the minority carriers from recombining. The technology is also carrier-selective, facilitating the collection of electrons as well as holes, meaning it can be applied on both sides of the wafer. Several research

Source: Jolywood

Passivation is the key: The crux of the TOPCon structure is passivating the surface, especially the rear.

Comparison Cell Technologies' Production Characteristics

Cell technology	Crux of process	Predominant wafer type used	Passivation			Metallization	Additional steps
			Side of the wafer	Dielectric	Application methods		
PERC	Replace aluminum BSF with surface passivation on rear	Mono / Multi	Front	Silicon Nitride	PECVD	Local BSF forming aluminum paste, floating busbar silver paste and front-contacting paste compatible for low-temperature firing	Laser contact opening, rear polishing
		Mono / Multi	Rear	Aluminum Oxide / silicon nitride (capping)	PECVD, ALD / PECVD		
		Mono		silicon oxynitride / silicon nitride (capping)	PECVD		
PERT	Front and rear are totally diffused and both surfaces are passivated	n-type	Front	Aluminum Oxide, silicon oxide, BSG / silicon nitride (capping)	PECVD, ALD, thermal, wet chemical, diffusion / PECVD	Employs silver pastes on both sides of cells and front side silver pastes is aluminum doped	Boron diffusion, front surface passivation, wet chemical based cleaning steps
			Rear	Silicon Nitride	PECVD		
PERL	Front and rear surfaces are passivated and rear surface is locally diffused at the metal contacts area	n-type	front	Aluminum Oxide, silicon oxide, BSG / silicon nitride (capping)	PECVD, ALD, thermal, wet chemical, diffusion / PECVD	Employs silver pastes on both sides of cells and front side silver pastes is aluminum doped	Boron diffusion, front surface passivation, laser based local doping, wet chemical based cleaning steps
			Rear	Silicon Nitride	PECVD		
TOPCon	An ultra-thin silicon oxide layer is applied that allows the charge carriers to "tunnel" through and a polycrystalline silicon is deposited over it, which is subsequently doped.	n-type	Front	Aluminum Oxide, silicon oxide, BSG / silicon nitride (capping)	PECVD, ALD, thermal, wet chemical, diffusion / PECVD	Aluminum doped silver pastes on the front side and special rear contacting silver pastes , both supporting low temperature firing	Boron diffusion, front surface passivation, wet chemical based cleaning steps
				Silicon oxide (thin)*	Thermally grown, chemical, deposited		
			Rear	Polysilicon*	LPCVD, PECVD, APCVD, PEALD, PVD		
HJT	The heterojunction is formed between a doped crystalline silicon substrate (n or p type, though the former is widely used) and an amorphous silicon layer of opposite conductivity (p or n type respectively).	n-type	Front / Rear	Amorphous Silicon	PECVD	Requires low temperature curing pastes, while plating is also an potential alternate	Special wet-chemical cleaning process and transparent conductive oxide deposition
IBC	Creating alternate regions with n+ and p+ doping on the rear side	n-type	Front	Aluminum Oxide, silicon oxide, BSG / silicon nitride	PECVD	Contacts of both polarities are rear side	Masking and cleaning processes

Source: © TaiyangNews 2021

** Used in combination*

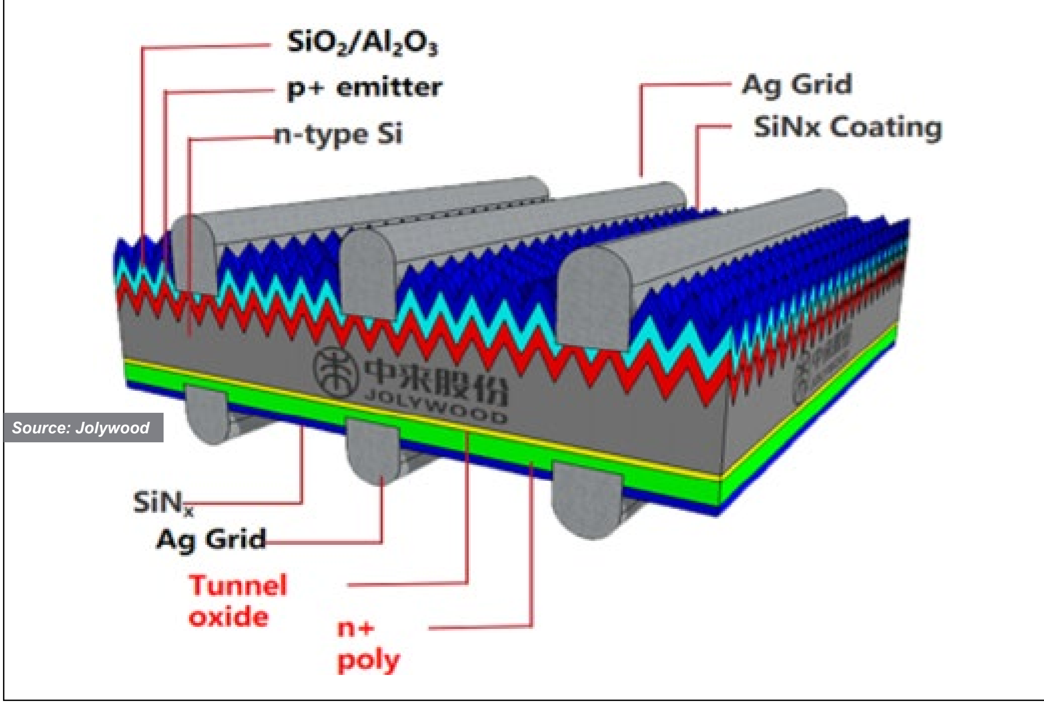
Key Characteristics: The most important differences between the various silicon cell technologies are the passivation mechanism and metallization scheme.

centers have christened the technology with different names: TOPCon, Monopoly, POLO contacts and so on. However, the industry, especially the Chinese PV community, picked up TOPCon as a common abbreviation for passivated contacts. To be more precise, the structure is adapted to the rear side of the n-type wafer. Here, an ultra-thin silicon oxide layer is applied that allows the charge carriers to "tunnel" through and a polycrystalline silicon layer is deposited over it, which is subsequently doped. This combination of stacked layers allows the electrical current to flow out of the cell almost without any losses. The silicon oxide provides excellent chemical passivation. The heavily doped polysilicon topping repels the minority charge carriers, thus providing good field effect passivation. The thin tunneling oxide has high selectivity; it allows the majority charge carriers to tunnel through at very low junction resistance, enabling the electrons to easily tunnel through the oxide. In addition to providing excellent chemical passivation and field effect passivation, the TOPCon structure provides good majority carrier selectivity and rapid carrier transport between the absorption and the doped layer.

2.2 Industrial TOPCon Structure

In principle, TOPCon is a structure formed at the surface of a semiconductor, which combines the functions of a passivation layer and a contact. However, making the concept work in standard crystalline silicon cell manufacturing, especially making it compatible with high-temperature processing, is what is tagged today as the TOPCon approach. The structure in principle can be applied on either side of the wafer and is also compatible with p- and n-type wafers. However, since polysilicon has a similar band gap as crystalline silicon, it results in larger absorption losses when doped polycrystalline is used on the front side. While there are methods to circumvent losses from unwanted absorption, they are not production ready yet as it involves sophisticated masking and etching steps. Thus, 'passivated contacts' is a term used mostly in reference to the rear side engineering in the industry. As to the question of which base wafer should be used, the effort of adding a TOPCon structure to a PERC structure doesn't produce enough 'bang for the buck' per se. As a result, the majority of the industry continues to use passivated contacts on the rear side of n-type wafers.

Here is the schematic of a TOPCon solar cell from China's Jolywood, a pioneer of this segment that has led the technology in high-volume manufacturing. The n-type base wafer features p+ boron emitter passivated with a stack of aluminum oxide and silicon nitride dielectric. On the rear, a very thin 1 nm tunneling oxide is topped with n+ polycrystalline silicon and silicon nitride stack, and both the surfaces are metalized with silver paste.



Source: Jolywood

Schematic: TOPCon in today's industrial perspective is to apply a stack of silicon oxide and a doped polycrystalline layer on to the rear side of n-type wafer featuring a passivated boron emitter.

Similarities between Passivated Contacts and PERC in Early Days

	Substrate	Thin oxide	Poly silicon	Metallization	Others
Passivated contacts	• P-type? • N-type?	• Wet-chemical? • UV? • Thermal?	• PECVD? • LPCVD? • in-situ doping? • Ex-situ doping? • Annealing?	• Evaporation? • Screen printing? • TCO?	• Cell structure? • Process flow? • Industrial maturity? • Yield? • Cost?
	Substrate	**Passivation**	**AlO_x**	**Metallization**	**Others**
PERC in 2014	• P-type? • LID?	• AlO_x:H? • Thermal SiO_2? • SiO_xNy:H? • SiN_x:H capping?	• ALD? • PECVD? • PVD?	• LFC? • Laser/chem. opening? • Evaporation? • Screen printing?	• Cell structure? • Process flow? • Industrial maturity? • Yield? • Cost?

Source: Trina Solar; graphic: © TaiyangNews 2021

Several questions: Similar to PERC at the time of its inception, there are several questions that need to be answered for passivated contacts on how to implement the technology.

2.3 TOPCon Developments at a Glance

Passivated contacts using a stack of silicon oxide and doped polysilicon is not a new concept. Such structures were first used in bipolar junction transistors in the 1970s in semiconductor applications. It was only a decade later — around early 1980s — that the approach was implemented for PV related applications. Well known Australian solar scientist Martin Green developed cell architectures using tunneling oxides and polysilicon stacks in 1983. The technology first saw commercial light in 2009 when SunPower introduced a tunnel layer passivated IBC cell structure. However, German research institute Fraunhofer ISE brought the technology to the fore in 2014, when it announced 23% efficiency on a small area and gave the technology a name — TOPCon. The research institute still holds the best cell efficiency of 25.8% for double-side contacted TOPCon structure. Adapting passivated contacts technology to the IBC structure, research institute ISFH has developed a cell architecture called POLO that has hit a record efficiency of 26.1% in 2018.

With the efficiency of the PERC, the standard as of today, expected to reach its limits soon, the industry is seriously evaluating the next evolutionary step — passivated contacts. On the other hand, passivated contacts as an approach is exactly at the same stage as PERC during its commercialization phase during 2014 to 2015. Many consider passivated contacts as the direct successor to PERC, because TOPCon qualifies for all those parameters and offers the same benefits PERC had over BSF. It has the same performance advantages, especially in improving Voc by about 20 mV and it also requires two to three additional process steps and the appropriate production equipment, depending on the base process. The industrialization of passivated contacts raises several questions, as did PERC in the past (see table).

According to a calculation from ISFH published in 2018, the theoretical ultimate efficiency of PERC is 24.5%, 27.5% for HJT, and TOPCon scores the highest at 28.75%, very close to the ultimate efficiency reached by monocrystalline silicon cells. This emphasizes the theoretical efficiency potential of the TOPCon architecture.

Comparison of Cell Efficiency Limits

nmax[%]	Electron-selective contacts						
	P-diffused n+	a-si:H(i) / a-si:H(i)	SiOx (thermal) /POLY-Si(n+) PECVD	SiOx (thermal) / POLY-Si(n+) LPCVD	SiOx (chemcial) / POLY-Si(n+) LPCVD	Siox / TiOy	MgOx
Al-p+	24.5 (PERC)	26.8	26.9	27.1	27.1	26.3	24.9
a-si:H(i)	24.7	27.5 (HIT)	27.7	27.9	28	26.8	25.1
SiOx /poly Si(p+)	24.9	28.1	28.3	28.7	28.7	27.3	25.4
SiOx /Si:C (p+)	24.9	28	28.2	28.5	28.6	27.2	25.3
a-si:H(i)/MoOx	24.4	26.5	26.6	26.8	26.8	26	24.7
MoOx	24.1	25.9	26	26.1	26.1	25.5	24.4
PEDOT:PSS	24.1	26	26.1	26.2	26.2	25.6	24.5

Source: ISFH, Table: © TaiyangNews 2021

Very close to the ultimate: According to ISFH's calculation, TOPCon has the highest theoretical efficiency potential of 28.75% among several configurations of high efficiency cell technologies.

3. TOPCon processing

The basic principle of passivated contacts is to apply metal contacts without patterning. In order to realize this in the real world, two steps are necessary – growth of interfacial silicon oxide and deposition of intrinsic polycrystalline silicon layers, which is subsequently doped. In principle, 3 additional steps are required when upgrading from n-PERT to passivated contacts. When compared to PERC, since TOPCon is typically employed on n-type, it requires boron diffusion for emitter formation in subsequent cleaning steps. While there are 2 integrated cleaning steps with PERC, TOPCon requires at least 3 steps. Even BSF followers, a rarity these days, can bypass PERC and directly upgrade to TOPCon.

There are several variants of the TOPCon process flow. It can start from emitter formation or from rear surface engineering. Given that the technology is in its nascent stages and that there is more than one way that each step can be accomplished, the process sequence and the steps involved are also varied based on the technology selected. And these options present themselves right after the most common first step of any cell processing — saw damage removal and texturing — accomplished with wet-benches. The majority of the TOPCon manufacturers seem to have chosen the path of emitter formation. This method enables manufacturers to deal with the high thermal budget involving the boron diffusion step right up front, sparing the rest of the cell structure, especially the very thin tunneling oxide, from high temperature processing. Boron diffusion can also be achieved through ion implantation, in which case the above restriction does not apply. Companies like Semco Smartech, however, have developed a process that starts with rear surface engineering, eliminating the dedicated annealing or activation step altogether. “Making tunneling oxide work equally effective even after boron diffusion is the key,” said Raymond de Munnik, CEO of the France based company, “And we demonstrated it,” he emphasized, while expressing his pride in Semco’s deep TOPCon process knowhow. On the other hand, he also acknowledges that the industrial practice is to start with emitter formation, followed by removing the respective glass with single-side etch. Then the rear surface is polished, again using wet-benches.

Formation of thin tunneling oxide is the next step. There is also a wide range of tunneling oxides to choose from. A few early industrial adopters used a wet-chemical method to generate an ultra-thin oxide. Subsequently, other methods were developed — plasma-assisted oxidation, wet-chemical hydrochloric acid oxidation, wet-chemical nitric acid oxidation, thermal oxidation, and UV/O3 anodization. The thickness of the tunneling oxide, however, remains an important attribute. While there is no standard as of now, according to literature, tunneling becomes less likely in the case of thicker oxides since tunneling is assumed to take place when the oxide is thin, say less than 2 nm. Thermally grown silicon oxide is not only known to provide a superior chemical passivation quality, but even the setup and the process are easy to accomplish. It can also be integrated into the subsequent polysilicon deposition. With cell makers focusing more on simplifying the process flow, integrated application of oxide and polycrystalline silicon in one go is preferred, if the tool platform permits. However, Centrotherm believes in decoupling the steps, as it not only reduces costs, but also improves the film quality. For polycrystalline deposition, the core of the TOPCon process, almost every deposition technology used in PV is promoted here — **LPCVD**, **PECVD**, **APCVD**, **ALD** and **PVD** — in varying degrees of availability. The deposited polysilicon has to be doped, and there are options here as well. Jolywood, for example, has been known to employ ion-implantation for realizing n+ doping of the polysilicon, which can also be accomplished in tube diffusion furnaces using a POCl process. While the ion-implantation avoids PSG etch in comparison, it requires activation of the dopant as an additional step, which is also the case with another option of in-situ doping as facilitated by certain machine platforms. It doesn’t come as a surprise that in-situ doping is attracting a lot of attention with the simplification that it brings to processing steps. The TOPCon structure applied on the rear side also results in a parasitic deposition on the front side, which needs to be removed through wet processing, though the degree of effort for stripping the polysilicon layer depends on the deposition technology of choice. The front surface is passivated with a stack of aluminum oxide and silicon nitride, deposited using either PECVD alone or a combination of ALD and PECVD. The passivated contact stack is also capped with silicon nitride using PECVD. Silver contacts are applied on both sides followed by firing to finish the last leg of the cell manufacturing process, preparing the cells for IV testing and sorting.

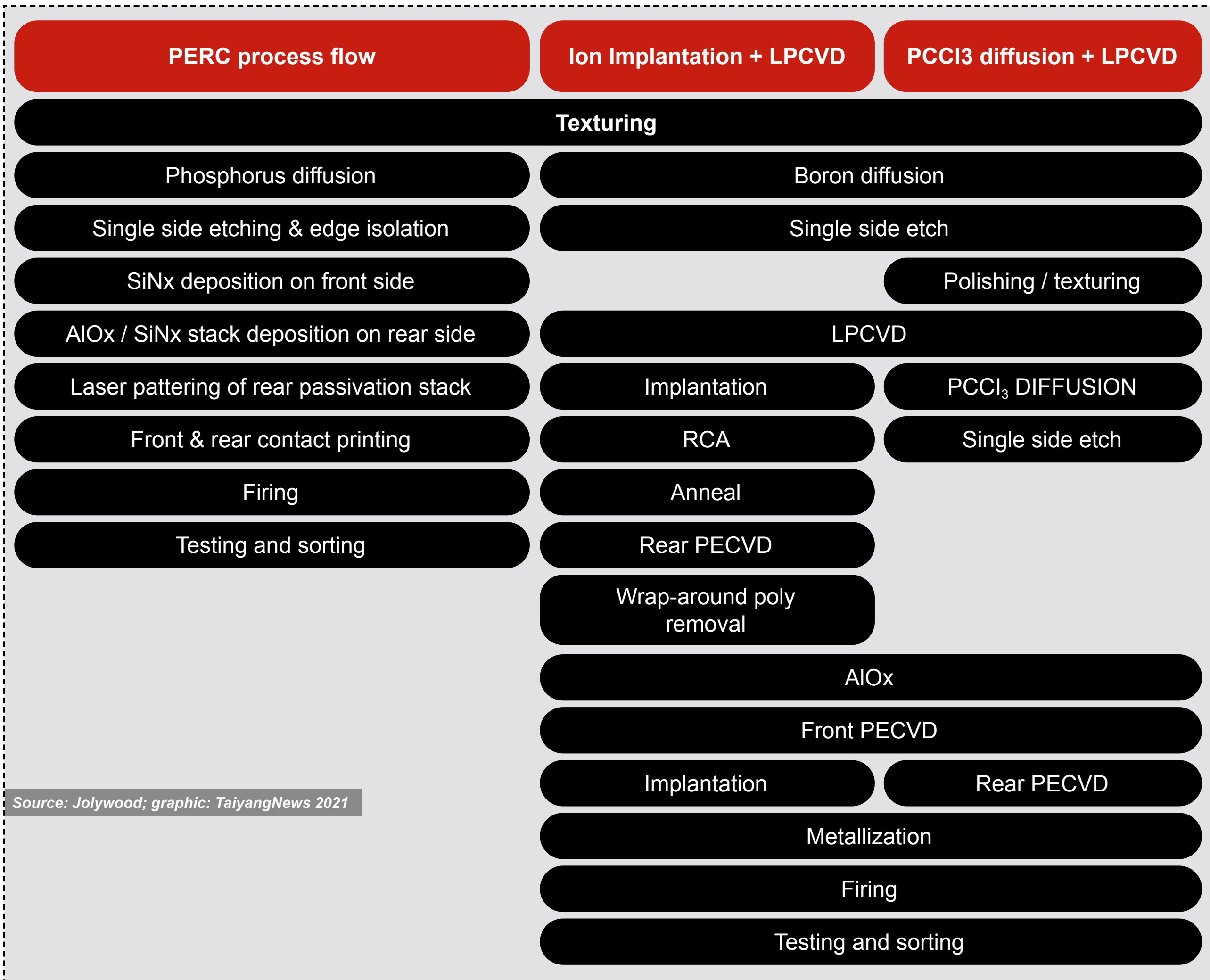
3.1 Deposition Technologies

TOPCon is no doubt more complex and an extensive process. However, the additional process steps that are required over PERC are about 3 to 4. These are: boron emitter formation, applying tunneling oxide and polysilicon films and doping the latter, and the cleaning steps originating from additional diffusion steps. When it comes to manufacturing of passivated contacts, the core of the process lies in three steps — application of interfacial oxide, deposition of intrinsic polycrystalline silicon layers, and doping of polysilicon.

As mentioned above, **LPCVD**, **PECVD**, **APCVD**, **ALD** and **PVD** tools from various vendors are promoted for the core job of producing passivated contact cells. However, LPCVD is the most favored method as of today.

3.1.1 LPCVD

LPCVD is a widely used process in the semiconductor industry for depositing polysilicon and even doped silicon, exactly what is also needed for TOPCon. With a strong semiconductor industry background and the technology being readily



Typical process flow: While there are several variants of the TOPCon process flow, applying a stack of silicon oxide and doped polysilicon layers are the crux of the cell process.

available, several European equipment vendors turned to LPCVD as the first choice. This thermal process is used to deposit thin films from gas-phase precursors operating at vacuum. The reduced pressure during the process helps reduce unwanted gas-phase reactions and improve film uniformity across the wafer. All LPCVD tools promoted for passivated contacts today enable the growth of tunneling oxide and polysilicon in the same run without breaking the vacuum. And in-situ doping of polysilicon is also offered by all these tool vendors, at least as an option.

Semco, also a company with in-house polysilicon deposition experience for its semiconductor clientele, developed an LPCVD solution for TOPCon. The tool platform of the company has even alleviated major shortcomings of the LPCVD technology. A major change that the company brought in was to replace the breakable quartz reactor with a stainless steel chamber.

There are many challenges that crop up with wafers growing in size, CEO de Munnik emphasized in his presentation at the CSPV 2020 virtual conference organized by TaiyangNews. He explained that wafers can have a bow and/or a counter bow. The dynamic processing environment in the reactor, especially during the heating-up phase, may lead the wafers to shake slightly, causing breakages. Then, the typically employed back to back loading – 2 wafers in a single slot – poses the risk of the precursor penetrating the gaps between the wafers, causing parasitic deposition.

Semco's solution for this issue is to place the wafers horizontally in the reactor. The company claims 10 years of mass production experience with this approach, a design originally used for string ribbon wafers that did not have a fixed form factor. According to de Munnik, the lessons learned from this experience was that, the bending/bowing being a function of gravity even during the temperature ramp-up phase, placing the wafers horizontally enables them to move freely in both the radial as well as axial directions. This takes out the stress from the processing environment. In addition, the horizontal orientation aligns gas distribution parallel to the wafer surface, while offering higher flexibility to fine tune the process window. Above all, it addresses a key issue of the LPCVD, the wraparound. While this approach would not eliminate the wraparound completely, it does afford better control or pushes it down to a predictable level at least, according to de Munnik.

Integration is the next checkbox for the company. Semco, with its considerable experience in selling thermal oxidation furnaces for growing thin oxides, has been able to integrate that knowhow into the LPCVD platform. Providing in-situ doping completes the final step of integration. The LPCVD platform of the company, called HORTUS, accomplishes all necessary processes required for establishing the passivated contact structure on the rear side of the cell. The platform first thermally grows silicon oxide and in the same run, without breaking the vacuum, deposits the intrinsic polysilicon and applies doped polysilicon in the second half of the deposition.

Improving throughput is an ever-extending goal for equipment makers, and manufacturers of course would like to load more and more wafers per batch to improve the overall productivity. What that means is more and more wafer slots are desired. But, there is a physical limit to the number of slots that can be added. A reactor cannot keep increasing in diameter in regard to the wafer size, as well as the length. “This is now well understood, as multiple customers have experienced difficulties with M10 or G12 wafers in this vertical loading configuration, especially with dropping yields,” said de Munnik. Addressing the needs of increasing throughput, Semco adopted a self-determined inter-wafer slot distance (pitch) of 3.2 m, which is a significant improvement over the historical loading practice, underlined de Munnik. This design has enabled the company to continue with the same pitch of 3.2 mm, even for high-temperature boron diffusion. He further emphasized that this approach facilitates processing thin wafers, down to 120 μm, indicating the preparedness of the company's solutions for upcoming developments in the area of thinner wafers. At the moment, the larger M10 and G12 wafers measure 170 μm and above in thickness. Starting initially with 1,400 wafers per reactor, the company is now able to load 1,800 substrates of even larger sizes per reactor. The overall design has not only eased wafer loading in the cassettes, but the cassettes themselves are locally made in China, easy to clean and replace – evidence of the cost-effectiveness of the solution.

All steps at high pace: Semco's LPCVD platform, called HORTUS, accomplishes all the necessary processes required for establishing the passivated contact structure on the rear side of the cell, and still supports a very high throughput of 5,700 G12 wafers per hour.

Semco's HORTUS LPCVD platform comes in a 6-stack furnace configuration. The tool accomplishes all 3 processes — tunneling oxide growth, polysilicon deposition and in-situ doping of polysilicon film that is capable of processing 10,800 silicon substrates per production cycle. This translates into an hourly throughput of 5,700 with G12-size wafers, while the capacity goes up to 6,000 when processing M10 wafers. The above numbers are with reference to a polysilicon layer thickness of 160 nm. Semco has been an equipment partner for early adopters of TOPCon, such as Korea's LG, and the company claims more than 4 years of mass production experience with its tool. It has also supplied "several" of its toolsets to leading manufacturers that are operating with high production yields of up to 96% in mass production, according to de Munnik.

Centrotherm is another important equipment maker that also has 'a foot in' in the supply of processing tools to the semiconductor industry. The company also has an LPCVD based solution on offer for TOPCon cell production. Employing LPCVD, especially to deposit undoped polysilicon, has been the main route to realize TOPCon structure in production, according to Josef Haase, senior technical director of the company. While its first-generation tools were aptly designed to accomplish these basic tasks, the company added the in-situ doping feature to its platform to simplify the process. However, opting for in-situ doping reduces the throughput. While undoped poly can be accomplished with half pitch loading of 1,600 M6-wafers and 1,200 of M10 as well as G12 wafers per tube per batch, the in-situ process requires wider spacing, meaning a full pitch of 4.76 mm. Thus, the batch size is limited to 800 M6-wafers and 600 of M10 and G12 wafers. And it also makes the reactor more complex with the additional handling of gaseous mixtures of silane and phosphene or diborane. It is still worth the effort; consecutive doping not only eliminates the POCl diffusion step entirely, PSG etch can also be avoided. With the in-situ step, the dopant is already evenly spread, which just requires a short RTP activation step. The annealing or activation step is very well accepted by the manufacturers, given the low prices of such simple thermal treatment furnaces. And with proper optimization, the step can also be integrated into the firing profile.

Centrotherm, unlike others, is not in favor of integrating the step in one tool when it comes to tunneling oxide growth. “Is it possible? Yes, very well possible,” said Haase. However, one has to look at what is less expensive. Growing tunneling oxide at 650°C is feasible, but if higher temperatures are desired, then 2 furnaces would be more cost effective, he explained. Doing tunneling oxide as well as polysilicon in one tool, in addition to increasing the process time significantly, also limits the batch size to 800 wafers, especially when opting for in-situ doping, while 1,600 wafers loaded in half pitch configuration can be seamlessly accomplished for tunneling oxide alone. Then, the quality of the tunneling oxide grown in a clean environment compared to an integrated platform is better, said Haase. “Everybody does it externally, as it makes a lot of sense from a cost point of view as of now,” he added. While the tool platform supports integrated processing, it is the manufacturer’s prerogative in the end.

Centrotherm has introduced a brand new variant of c.DEPO X LPCVD system with 10-stack tube configuration. Similar to any other equipment maker, Centrotherm has scaled up the processing tools to accommodate larger wafers up to 210 mm side length. Depending on the opted process recipe, doping configuration and process integration, the tool supports a throughput of up to 6,000 wafers per hour. The thickness of the polysilicon is yet another parameter that influences throughput, the prevailing standard for which is between 100 and 150 nm. Centrotherm has already supplied its LPCVD furnaces to “a few” cell makers.

Laplace is another notable LPCVD supplier in China, primarily focused on TOPCon with larger and thinner wafers. Incorporated in 2016, the company supplied its first LPCVD pilot tool in 2017. Eventually, Laplace shaped itself up to be a one-stop shop for all thermal processing needs for TOPCon, offering diffusion furnaces for boron and phosphorus, LPCVD for depositing intrinsic as well as doped polycrystalline, PEALD for applying passivation layers on boron emitter, and annealing furnace to activate dopant in case of in-situ doping. The year 2020 was a pivotal one for the company, when Laplace was contracted for a GW scale supply of key TOPCon equipment from an undisclosed cell maker. In parallel, the company has won bids to supply processing tools for TOPCon pilot lines from other PV manufacturers, according to John Jiang from Laplace). As for LPCVD, the company is offering 2 different product platforms – one for depositing intrinsic poly layer, while the other accomplishes in-situ doping as well. The former process sequence required phosphorus diffusion, which was also developed by the company eventually. The doped poly approach requires an annealing furnace, which as well is supplied by Laplace. The boron emitter also needs to be passivated, for which the company has developed PEALD tools.

Laplace is also a strong advocate of processing wafers horizontally for the same 2 reasons – to keep the wraparound within limits and to address breakage issues associated with larger wafers. In order to overcome quartz tube deformation issues, Laplace uses paddles to support the boats during the processing so that the boats are not directly placed in the tube, an approach it originally developed for boron diffusion. Sparing the details, Laplace says it has optimized the process to improve the lifespan of the quartz-ware – to least 4 months – which according to Jiang accounts for 1.5% of the costs, and the company plans to reduce it to 1% by enhancing the life further.

As for the throughput, for wafer sizes below 190 mm, each tube can be loaded with 2,000 wafers. The tool requires 80+ minutes to accomplish the deposition of intrinsic poly, which goes up to 3 hours with in-situ doping. The loading capacity drops to 1,600 in case of G12 wafers. And the net throughput depends on the choice of number of tubes and process recipe. For reference, the 5-tube configuration can process above 3,300 of M10 wafers with in-situ doping. Laplace has an installed capacity of about 3 GW.

Polar PV is a Chinese equipment maker that, while not so well known in the past, is active in supplying various deposition and processing equipment for PV as well as the semiconductor industry. The company is also offering process development solutions for high efficiency cell architectures including TOPCon, HJT and IBC. For the TOPCon application, the company is offering two different equipment platforms — PVD and LPCVD. The LPCVD platform of the company accomplishes the growth of tunneling oxide and deposition of polysilicon. From loading to unloading, the process is accomplished in 13 steps in an average cycle time of 110 minutes. However, some companies have even managed it in 100 minutes, notes the company. One way to reduce the cycle time further is through the optimization of polysilicon layer thickness, which is currently between 80 to 150 nm. Polar PV's LPCVD has a throughput of 3,600 wafers per hour, applying 1 to 1.5 nm of silicon oxide and 100 nm of polysilicon. Polar PV claims that it has supplied LPCVD tools for Jolywood's entire 2.4 GW production capacity.

S.C New Energy, the leading Chinese equipment supplier, is also offering 2 solutions for TOPCon, and LPCVD is naturally the first. Called LD-420, the company's LPCVD furnace is built with a 6-furnace stack in its standard configuration, while a tool with 5 or 4 tubes can also be ordered. The tube has an inner diameter of 420 mm, enabling the processing of wafers up to G12, while the company would also consider a special request to configure the furnace to process further larger wafers of up to 230 mm side length. The company is using a double-layer quartz tube structure with water-cooled tube sealing technology. Each tube has a 2,200 mm flat zone that accommodates 1,600 wafers in a back-to-back loading configuration following half pitch arrangement of 2.38 mm. The tool supports quite a wide range of low-pressure processing environments from 15 to 600 Pa. This LPCVD furnace is designed to accomplish three important process steps of the TOPCon process — growing tunneling oxide with thickness between 1.4 and 2.2 nm, polysilicon layer from 80 to 200 nm, and in-situ doping. However, S.C New Energy considers 150 nm as the polysilicon layer thickness for indexing the process with the spec for thickness uniformity deviation of 3% within the wafer and run to run, while 4% is given for wafers of the same batch.

Tempress also supplied several of its LPCVD tools during the early days of TOPCon's commercialization. However, the company is now under new ownership of Innovation Industries after it was separated from Amtech Group. The plans for its PV business are not known and the company has not responded to our enquiry. Similarly, several Chinese equipment vendors have popped up in China that are offering LPCVD tools such as NAURA and Red Sun. The companies, however, have not responded to our enquiry.

3.1.2 PECVD

Addressing the shortcomings of LPCVD, especially the wraparound, the PV industry is increasingly getting interested in PECVD technology. Formerly, Meyer Burger spearheaded the development of PECVD for TOPCon applications, but there have been no recent updates since the company's exit from the open market. On the other hand, another leading European equipment vendor, Centrotherm, in cooperation with Fraunhofer, is also developing a PECVD based solution. S.C New Energy and Jinchen are 2 Chinese companies that have forayed into PECVD solutions for TOPCon.

Automation experts **Jinchen**, well known in the module production equipment business, ventured into TOPCon solutions as part of their entry into cell production equipment in 2019. It started working on 2 technologies – HJT and TOPCon – in parallel and handling them separately through different subsidiary entities, albeit based on the same technology platform –PECVD. For HJT, the company is cooperating with the European consulting firm, H2GEMINI, while for TOPCon it is working with a domestic partner, Ningbo Institute of Materials Technology & Engineering. The company is focusing on the tube PECVD tool platform for the latter. Unlike many others operating in this field, Jinchen is only supplying the key deposition equipment for the technology and printing solution through another subsidiary, but not the complete line.
According to Jinchen, TOPCon is getting increased attention starting this year; PERC followers, under pressure from the developments in the HJT segment, are leaning more and more towards TOPCon, which is a very natural way to extend the lifespan of the PERC lines with efficiency upgradation and TOPCon has everything that a new technology requires. As for reasons behind opting for PECVD, the technology brings down the wraparound to negligible levels. Wraparound, the main reason TOPCon has never managed to overcome severe yield problems, has darkened its prospects for widespread adoption. And the additional wet-chemical treatment required post LPCVD to remove the wraparound adds to overall cell production costs. PECVD, in addition to addressing these issues, also supports higher deposition rates.

Charecteristics of LPCVD Systems used for TOPCon					
Company	**Centrotherm**	**S.C. New Energy**	**SEMCO**	**Laplace**	**Polar PV**
Model	c.DEPO X	LD-420	HORTUS LPCVD	-	-
Technology	LPCVD	LPCVD	LPCVD	LPCVD	LPCVD
Applications	Tunneling oxide +intrensic polysilicon+ in-situ doping	Tunneling oxide, polysilicon, in-situ doping	Tunneling oxide, polysilicon, in-situ doping	Tunneling oxide +intrensic polysilicon+ in-situ doping	Tunneling oxide + polysilicon
Suitable Fab configuration	-	-	-	-	-
Wafer orientation	-	-	Horizontal	Horizontal	-
Equipment configuration	10-stack tube	4-6-stack tube	6-stack tube	5-6 stack tube	-
Wrap-around	-	-	minimal	minimal	-
In-situ doping	-	Yes	Yes	optional	No
Wafers per tube	1,600 - half pitch loading, 800 full pitch	1,600	1,400	2,000	-
Growth rate	-	-	-	-	-
Oxide layer thickness	-	1.4 - 2.2	-	-	1 - 1.5
Polysilicon layer thickness	100 - 150	80 - 200	160	-	100
Throughput (WPH)	6,000	3,000*	G12: 5,700 M10: 6,000	G12: 7,200 M10: 8,000	3,600
Mechanical Yield (%)		-	0.96	-	-
Film uniformity	-	3% within wafer, run to run; 4% wafers of same batch	-	-	-
Footprint	-	-	-	-	-
Uptime (%)	-	-	-	-	-
Commercial status	Ready	-	Ready	Ready	Ready
Already in mass production	Finished testing	-	Yes	Yes	Yes

**In-situ doping; ** Ex-situ doping*

Source: © TaiyangNews 2021

Different configurations: The current crop of LPCVD tools for the TOPCon application are not only capable of handling all required tasks for rear surface passivation, but are also available in different configurations.

The tube PECVD tools of the company have passed the pilot verification at several leading cell makers, attaining an average mass producing efficiencies exceeding 24% with best production efficiencies already reaching 24.5%. Very recently, Jinchen's key research partner Ningbo Institute has announced a record efficiency of 25.53% for a TOPCon cell. As it is with any PECVD reactors, the throughput depends on the number of tubes integrated into one frame. Jinchen's production solutions have the flexibility to choose the number of tubes between 4 and 6; accordingly, the approximate throughput also varies from 5,000 to 6,000 wafers. These tools are also designed in a way that they can accommodate all the mainstream wafer sizes from M6 to G12. The PECVD reactors of the company can accomplish the deposition of polysilicon, which is doped in-situ. In parallel, Jinchen is also developing a of so called a “two-in-one” that can accomplish the applying tunneling oxide topped with in-situ doped polysilicon layer in same machine. The company recently announced that it attained breakthroughs in this integrated reactor design, which it characterizes one of few developments made in China before their overseas peers, quoted a Chinese press release. Characterizing developments with metallization pastes as key governing factors for further reduction in polysilicon film thickness, Jinchen says that it’s are continuing strong collaborations with metallization paste suppliers to develop compatible paste solutions.

S.C New Energy, for almost the same reason as Jinchen, also developed a PECVD reactor for TOPCon. The horizontal reactor of the company, named PD-520, closely resembles the LPCVD tool of the company in terms of configurational aspects. It also comes with the option to choose 4 to 6 tubes in one reactor shell, while the highest number is standard. Each tube has a diameter of 520 mm that is compatible with wafer sizes from M0 to G12, and optionally can also accommodate even larger wafer sizes of up to 230 mm side length. However, the loading capacity per graphite boat is specified as 704 M6 size wafers. S.C New Energy is promoting the system as so called 4-in-one, capable of accomplishing applying tunneling oxide, intrinsic and doped polysilicon films and mask layer making it compatible with different process sequences for TOPCon production. It has a rated throughput of 5,600 wafers per hour resulting in film uniformity with a rated deviation of 5% within a wafer and substrates of the same batch, while even tighter deviation is realized when comparing the wafers from a different batch. The in-situ doping process can be optimized to realize a wide range of sheet resistance of the n+ surface ranging between 40 and 100 ohm/sq.

Centrotherm also started working on a PECVD based solution for TOPCon several years ago in cooperation with Fraunhofer ISE, Germany. The project, however, was put on the backburner due to an unexpected fire accident at the research center in 2017, activity was resumed in 2019.

Speaking at the TaiyangNews High Efficiency Cell Conference, Jochen Rentsch, head of department production technologies at ISE, gave a summary of the recent findings. The TOPCon process was done on the industrial PECVD tool using Centrotherm’s c.PLASMA PECVD with 40 kHz direct plasma, which is well known in the industry for SiNx and AlOx deposition. The tool can accomplish in-situ doping as well. Rentsch emphasized that the platform, in addition to achieving high process uniformity along the boat, has achieved high deposition rates up to 12 nm/ min leading to cycle times of 8 to 12 minutes in the lab setting. The numbers specified above are related to relatively thicker polysilicon films, mainly to be compatible with the current crop of metallization pastes. However, with the developments taking place in the paste segment, Rentsch is optimistic about thinning the layers down which will not only reduce the cycle times, but also improve the bifaciality of the technology. ISE has achieved an implied voltage of 740 mV — a good metric for passivation quality — and further confirmed record lifetimes with very low J0 values of 0.2+/-0.12 fA/cm^2 on a planar surface. Rentsch provided a few industrialization guidelines for TOPCon. It is observed that the composition of the SiNx layer capping the TOPCon layer on the rear has a significant effect on the rear passivation, and SiNx films with a refractive index between 1.95 and 2.05 have been found to have a big impact on the passivation attributes. As for the rear metallization, better contacts with low contact resistance are attained at higher temperatures and contact resistance of 1 mohm/cm^2 is indicated as the target value to be attained. As for emitter optimization, the research group evaluated several boron diffusion profiles and found out that higher the sheet resistance, better the Voc, which is quite evident. However, with an increase in the firing temperature, the Voc decreases with all emitter profiles. In a toss-up between the firing temperature and emitter sheet resistance, a good compromise needs to be made to achieve optimum passivation quality. It was concluded that TOPCon cell is strongly limited by the front side.

Acknowledging the trend towards batch type PECVD, Semco is also working on the technology for TOPCon applications.

Source: Centrotherm

Also taking the PECVD route: Centrotherm, with its longtime expertise with PECVD, is tweaking its PECVD platform to support TOPCon cell processing

3.1.3 PVD-based Technologies

Technically falling under the PVD category, Jietai prefers that its technology be called POPAID, which is short for Plasma Oxidation and Plasma Assisted In-situ Doping. Indeed, the technology is more than PVD; it combines PVD and plasma oxidation in one tool platform. Jiangsu JTech Photoeletric Corp LTD (Jietai) has been working on solar equipment supply for about a decade now, with its initial focus on dry etching tools mainly designed for multicrystalline. In 2019, the company started working on its PVD based solution with an aim to address the shortcomings of other deposition technologies, especially wraparound. The company's tool performs all necessary steps for TOPCon — formation of tunneling oxide, polysilicon deposition and in-situ doping.

The company uses linear RF plasma source for oxidation, which according to CEO of Jaitai Quanyuan Shang supports higher throughput, low damage and offers a higher degree of control. The throughput of the reactors is wafer size sensitive; it can process 10,000 G1 wafers per hour, dropping to 8,000 when processing M10 wafers. "The goal is to get 1 GW with two parallel lines (machines), that's how we sized the tool," said Shang. This throughput is at a polysilicon layer thickness of 100 nm. As one can expect, such a system is quite long, measuring 23 m in length. The tool has a scheduled maintenance cycle of 1 month, which the company is expecting to stretch to 2 months. Jietai is the equipment partner for Jolywood for its J-TOPCon 2.0 technology that is based on POPAID. Jietai has built one production tool so far and is expecting to ship POPAID tools of 5 GW by the end of this year, mainly to Jolywood. "We are pretty much sold out for this year" said Shang. The company is ramping up its production facility, meaning it would honor the orders from others next year.

Polar PV seems to closely follow the reactor design of Jietai and presented its inline vertical magnetron sputtering PVD system at PV CellTech 2021 virtual conference. The tool is designed to process a carrier with 60 cell slots in 6 x 10 configuration with a cycle time of 40 to 50 seconds. The tool is designed to accomplish all necessary steps for the TOPCon process — applying silicon oxide film, topped with in-situ doped polysilicon layer deposition. Even then the number of processing steps is considerably

More than PVD: Jeitai has developed a hybrid technology platform called POPAID that essentially combines PVD and plasma oxidation to address the shortcomings of prevailing deposition technologies for TOPCon.

reduced compared to LPCVD. The reactor setup is equipped with a low energy oxygen plasma oxidation chamber for the formation of tunneling oxide in a pure gas plasma environment. The ionization source is also maintenance free. The amorphous silicon layer, deposited using rotary silicon targets and in-situ doping, is accomplished by the introduction of doping gas.

PVD has several advantages over the incumbent LPCVD. The first and foremost, according to Polar PV, is the low cost of operation and low maintenance. This cost saving stems from the fact that this process does not involve quartz-ware, which is a major cost driver for the LPCVD process. Moreover, being a single-side process, wraparound becomes less of an issue, further aiding cost savings. Polar PV's PVD tool supports throughputs of up to 10,000 wafers per hour.
Energy consumption is another important means to reduce costs where the PVD shines through. Polar PV highlights that PVD uses 77% of the energy for coating and 16% for heating. In contrast, these figures are 34% and 45%, respectively, in the case of CVD. What this means is that energy utilization in PVD is far better than CVD, i.e., it is utilized where it matters more.

PVD also scores high in terms of process consumables. It uses silicon targets that are far cheaper than the silane used as the precursor in LPCVD. On the flip side, PVD has a high CapEx and a larger footprint.

Von Ardenne, with several decades of experience in building PVD reactors, has also been developing a TOPCon PV solution based on this technology. The German company's solution for passivated contacts is based on sputtering of amorphous silicon on silicon oxide — still in the development phase, but with encouraging first results nonetheless. Once ready, Von Ardenne plans to implement the process on its high-throughput PVD tools platform, currently capable of processing over 10,000 wafers per hour.

3.1.6 PEALD

Leadmicro has developed a new technology called PEALD, which the company abbreviates as Plasma Enhanced Atomic Layer Deposition. It is a hybrid platform combining advantages of ALD and plasma assisted deposition methods. In fact, Leadmicro was the first to introduce the technology. The company is mainly promoting its ZuRong (ZR) series industrial batch furnace, which is specially tailored for TOPCon related applications. The competitive advantages of ZR5000X2 models, according to the spec sheet, are its ability to support deposition of various oxide films and ALD nanolaminates with dedicated in-situ doping. The precise control of the process enables achieving desired energy bandgap, band alignment and resistances, thereby effectively passivating the surface and providing good carrier selectivity. The automation integrated into the machine platform supports accomplishing all the necessary steps of rear passivation in TOPCon, i.e., generating tunneling oxide and in-situ doped polysilicon in one go. The product supports different throughput levels depending on the wafer size; when processing M6 wafers, ZR series has a rated throughput of 4,200 wafers per hour, while the processing ability drops considerably to 2,800 level when processing larger silicon substrates (M10 and G12). The deposited films have high uniformity with a deviation of 3%. The tool has a rated uptime of 98% and keeps the mechanical yield losses less than 0.05%.

The company's ZR5000X3 system is a dual side depositing system. In PERC applications, the tool is equipped to apply a stack of aluminum oxide and silicon nitride on the rear, while also depositing silicon nitride on the front. The system is also capable of single side processing if desired, in case of which the throughput simply doubles. According to Leadmicro, the tool is also compatible with depositing TOPCon structures.

3.1.7 APCVD

Schmid from Germany is the only company to have an APCVD based solution for passivated contacts. One benefit of using an APCVD system is that it allows the use of multiple injector heads in series within a single system. The system delivers a throughput of up to 4,000 wafers per hour depending on the thickness of the layer to be applied. Schmid says its product can also support in-situ doping; however, the tunneling oxide would need to be applied externally.

Two notable advantages of the APCVD process are: a) it is a simple atmospheric process, and b) that it does not cause wraparound. According to Schmid, its APCVD solution eliminates one processing step from a total of 8 compared to using PECVD or LPCVD.

The technology, though, has somehow escaped the attention of TOPCon makers. One reason, according to Schmid, is its reluctance to supply free demo tools.

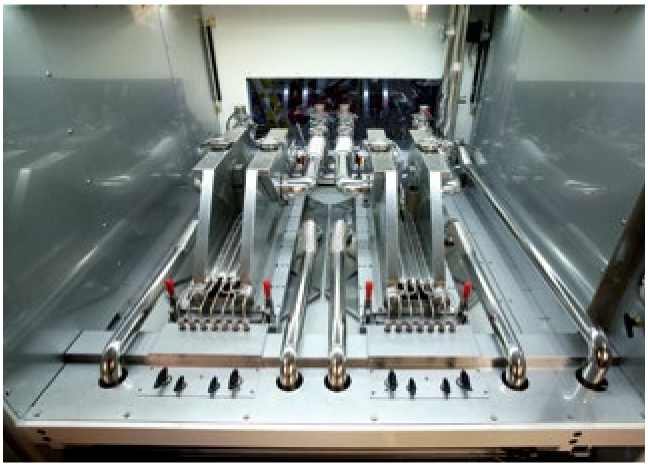
3.1.6 Comparison of Deposition Technologies

Banking on its privileged position as the most preferred deposition approach in the semiconductor industry, LPCVD was the most widely adopted even for TOPCon during its initial days of development. The fact that it allows the integration of tunneling oxide growth in the same chamber is a plus. From a process point of view, according to de Munnik from Semco, it was not easy to achieve tunneling oxide uniformity in order to prevent any interstitial defects between the different layers, which was initially the case with chemically grown silicon oxide, especially in mass production environment. The ability to support in-situ doping has also helped reduce the number of process steps.

Jolywood, the company with the highest TOPCon capacity of 2.4 GW, adopted LPCVD for polysilicon deposition for the same reasons as above. However, Jolywood's approach is a slight departure from the normal, in that it uses ion-implantation instead of diffusion for n-type doping of the polysilicon layer.

The technology is not without its shortcomings. To start with, the processing sequence in LPCVD-based manufacturing is quite lengthy. For example, Jolywood's first generation TOPCon technology

Source: Schmid



Missed the spot: While APCVD is also a wraparound-free process, the technology has somehow escaped the attention of TOPCon makers.

based on LPCVD involves 12 steps, which is both lengthy and expensive. And replacing ion-implantation with diffusion doesn't yield any dividends either, albeit in-situ doping does help simplify the process to an extent.

One inherent operational disadvantage is cracking of quartz tubes. Given the huge variation between their thermal expansion coefficients (about 5 times), as the polysilicon layer grows thicker, the stress between the polysilicon and inner walls of the quartz tube grows high enough to cause breakage of the quartz tube. Interestingly, the thickness threshold for the polysilicon layer also varies by company: Centrotherm's Haase puts it at 250 µm, while Polar PV pegs the threshold at 400 µm. Considering the polysilicon deposition on the inner wall of the tube is about 90 to 120 nm per each run, which typically lasts about 1.8 hours, Polar PV estimates the tube survives for about 3,000 runs or 6 to 8 months of continuous operation. Silicon carbide liners help avoid the cracking of the tube, in which case a deposition of up to 5 mm is allowed, extending the lifespan several-folds, according to Centrotherm's Haase. However, with lead times ranging from several months to more than a year, silicon carbide is not an optimal solution as of today. To overcome quartz tube related failures, Semco has been using stainless steel reactor vessels.

Not just the quartz tube, but the quartz boats that hold the wafers during the processing also break due to the same mechanism as explained above. Polar PV's analysis of quartz debris from commercial production concluded that most of the quartz boat failures are at the joints and the average lifespan of these boats is typically 20 days or 150 runs, whichever occurs first.

Above all, the early industrial TOPCon process suffered from severe yield issues attributed to the so-called wraparound. Since the degree of this pseudo-deposition is quite dynamic, the chemical removal steps not only become complex, but also lead to severe yield issues. Semco claims its horizontal wafer processing method limits the wraparound to the edges, which is easy to be handled in subsequent wet-chemical treatment steps.

Keeping these shortcomings in view, equipment makers and PV manufacturers have been working on alternatives. Naturally, Jolywood moved on to its second-generation TOPCon technology (POPAID), reducing process steps to 9. This inline processing method, based on single-side deposition facilitated by in-situ doping, realizes high deposition rates. Among its many benefits, the first and foremost is that it is free from wraparound. With its sub-nanometer (0.1 nm) level of control, the deposition of tunneling oxide achieved is very uniform. The quality of the passivation layer is also high, as is evident from the measured rear side J0 value of 3.5 fA/cm2, which is lower than LPCVD and PECVD, emphasized Jolywood in its presentation at TaiyangNews High Efficiency Solar Technologies Conference. This approach has paved the way for high efficiency and yield, and also lower costs, according to Jolywood. While Jolywood would not reveal the exact details of the technology, its TOPCon 2.0 is most likely using a modified PVD technology.

As discussed in the PVD chapter, its advantages over LPCVD are many: single side deposition, meaning no wraparound; inline operation, high throughput, higher energy utilization, low operational costs due to avoidance of using quartz-ware. While a graphite carrier is typically used in PVD, a stainless-steel carrier can also be used, according to Polar PV. Using silicon targets also helps lower manufacturing costs. However, the CapEx as well as the footprint for PVD is high.

PECVD definitely scores high in this regard. More and more companies, including the ones that have been offering LPCVD tools, have now started developing PECVD based solutions. S.C New Energy is already offering its solutions, while Centrotherm is in the final stages. Semco also has plans to move in this direction. Jinchen, relatively new to this area, is also already testing its tools at customer sites. PECVD based solutions are precisely aimed at addressing LPCVD's limitations. Single side processing, superior uniformity, low maintenance and reduced costs are some of the advantages that it brings, acco rding to Centrotherm's Haase. The technology and tool platforms are very familiar with PV manufacturing, already being in use in silicon nitride and aluminum oxide deposition applications. However, according to Laplace's Jiang, when depositing doped poly, the ceramic insulation in the graphite boat becomes conductive after about 20 runs, which requires clearing to maintain the process

yield.
The only thing that's missing as of now is a track record in large-scale manufacturing.

PEALD is an interesting approach, although details are very sketchy at present. The technical specifications in Leadmicro's data sheets make a good first impression, and the company says it has already found a partner to evaluate the technology. If successful, Leadmicro's PEALD tool would not only provide the benefits of PECVD, but with even better tunneling oxide properties. One might recall how Leadmicro changed the PERC equipment business for aluminum oxide deposition tools.

APCVD has been around for quite some time, being in mass production for other cell technologies such as IBC and PERL. For the passivated contacts approach, the APCVD tool offers a simple process and supports good throughput. An APCVD based process flow also requires fewer steps. However, TOPCon aspirants neither seem to consider it viable nor are they likely to.

In summary, while LPCVD did manage to get adopted early, it is losing ground to other technologies given its wraparound issue. And while every alternative promises the advantage of single side deposition, no technology is truly wrapround free in reality, according RENA Technologies' Technology & Process Director Holger Kuhnlein. RENA is a supplier of wet-chemical tools required to clean the undesired deposition. And having tested the samples made with different technologies, "We can confirm that, irrespective of the deposition technology, emitter side always needs to be cleaned," said Kuhnlein, "though the degree of cleaning may vary from technology to technology," he added. All PECVD suppliers/supporters argue that the parasitic deposition with the technology is easy to handle. As of now, PVD, LPCVD, PEALD and PECVD are the four main competitors in the race, the last of which has earned higher number of believers at least on the equipment vendor side. Every approach has its own merits and shortcomings, nonetheless.

3.2 Additional process steps (compared to PERC)

While the core of TOPCon lies in deposition of tunneling oxide and the polysilicon layer, producing these cells, though not critical, does require some additional processing steps worth mentioning.

Wet-chemical treatment: While not necessarily aimed at TOPCon alone, the key developments taking place in the wet-bench area can definitely benefit from the improvements made for other cell architectures. While two production tools need to be adapted for the TOPCon process – BSG and single-side emitter removal tools –, improvements with other wet-chemical treatment steps are also important in the larger scheme of things. RENA has been improving its tool platforms for the batch tools used for saw damage etching and texturing. Presenting at TaiyangNews High Efficiency Conference, RENA's Kuhnlein mentioned that the most recent developments associated with these batch tools are the ability to accommodate larger wafers and process the carriers with high loading density. With improved wafer quality in general and developments in the field of additives, there is potential to eliminate the saw damage removal step from the PERC sequence altogether, which can also benefit TOPCon, according to Kuehnlein.

Another PERC development that can also help TOPCon is an optimized pyramid size and reflectivity. The current state of the art is a 1 to 3 µm pyramid size and 9.9 to 10.1% reflectivity with monoTEXH2.3. While there are approaches that can reduce the pyramid size from 0.5 to 3 µm and corresponding reflectivity of 8.9 to 10%, the latter is only achieved for a limited number of runs of about 20. RENA is working on a more stable process that can last for over 200 runs, realizing a pyramid size distribution of 0.5 to 2 µm and resulting in a reflectivity of about 9.3%.

RENA learned from its experience with HJT that cleaning after texturing has the potential to improve efficiency - up to 0.05% with PERC -, which can also be implemented in TOPCon processing.

In order to remove the wraparound, RENA is promoting an inline etching tool platform called InPolySide. During the alkaline single side etching step to strip the poly, the BSG on the emitter side of the cell prevents emitter etching and the process is precisely single sided, meaning the rear is left totally unaffected. After the stripping step, the glass is etched off.

Atmospheric dry etching: As an alternative to the wet-chemical solutions to remove the wraparound, Nines Photovoltaics based out of Dublin, Ireland, is promoting an innovative solution. The company has developed a proprietary process called ADE, which stands for Atmospheric Dry Etching. The company has been developing the dry etching process since 2010 as a replacement for the typically used wet-chemical processes used in PV cell manufacturing. What makes this technology unique is that it accomplishes dry texturing at atmospheric pressure, eliminating the need for vacuum and plasma, which are both key ingredients and cost drivers in typical dry etching technologies, underscores Nines Photovoltaics' CTO Laurent Clochard.

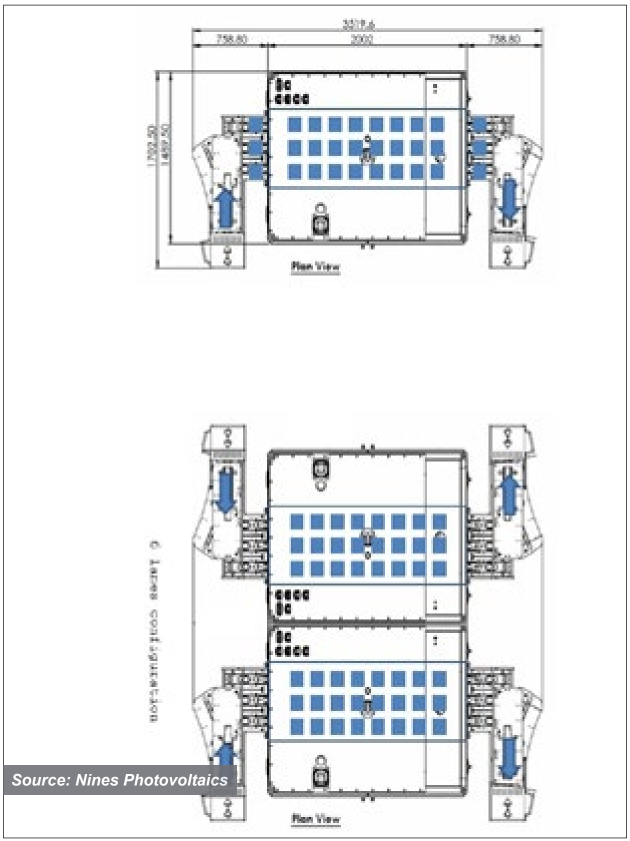
The reaction zone of the reactor is isolated from the rest by means of gas curtains. The process is accomplished in an inline fashion. The wafers are fed into the machines by means of a heated wafer carrier. An etching gas, which is fluorine (F_2), is thermally activated in order to dissociate the molecules. The etchant is then delivered to the wafers through a specifically engineered distribution device in order to create the required etch depth, texture and uniformity. Clochard clarifies that the technology has no special adverse impact on the environment. The thought of fluorine as an etching gas itself rings alarm bells about greenhouse gases. However, unlike the commonly used SF6 with high global warming potential for dry etching, the molecular fluorine used by Nines has zero global warming potential.

The tool, when it was introduced in 2017, was mainly designed for texturing, to be specific, for multicrystalline, in which the gains in reflection ADE are way higher than what can be achieved with the state of the art wet-chemical solutions. However, with the market shifting to monocrystalline, Nines Photovoltaics also turned its focus to the mainstream PERC and other advanced technologies. While the technology still carried forward its advantages in texturing, the ADE found an even more appealing application in TOPCon cell processing. Given its single side nature of the process, it can be effectively used for the removal of wraparound. "What's more?"

says Clochard, "You can opt for surface etching and/or edge removal, as the technology is also selective." That means Nines Photovoltaics' process not only accomplishes the etching without disturbing the underlying emitter profile, but it can also be engineered to remove the polysilicon on wafer edges, which is the major contributor to the shunts and yield losses. The tool has application even when the deposition processes are single sided.

Nines is currently operating a pilot line at its facility in Dublin and has partnered with Fraunhofer ISE for cell process development while also having supplied an R&D-scale system. The company is now ready with the production-scale platform, which is offered in 2 variants – ADE-3000 and ADE-6000. The latter processes wafers up to a size of M4 in six lanes and M6 to G12 in 4 lanes. The tool has a rated throughput of 12,000 and 8,000 wafers per hour, respectively, in a footprint of 12 m^2. The number of lanes is exactly half with ADE-3000, so is the throughput. These throughputs figures, however, are for to the texturing process, meaning the tool capacity would be much higher for single-side etching in TOPCon. "The amount of silicon that needs to be removed 10 times less than what you would for texturing," explains Clochard. The company is also willing to supply an R&D scale system with single lane of transport. As for costs, Clochard says that the costs are considerably lower than wet-chemical processes and the benefits are more apparent in larger scale production. This is facilitated by the fact that the etching gas can be produced on-site, according to Clochard.

Boron diffusion: One important additional process step compared to PERC is emitter formation, as today's TOPCon mainly focuses on the n-type wafer. The emitter is formed through boron diffusion, and



Source: Nines Photovoltaics

Dry and small: Nines Photovoltaics' atmospheric dry etching process called ADE that aptly fulfils the requirements of single-side etching in TOPCon to remove the wrap-around. The 3-lane tool, shown here, supports a throughput of 4,000 wafers in a small footprint of 6m^2.

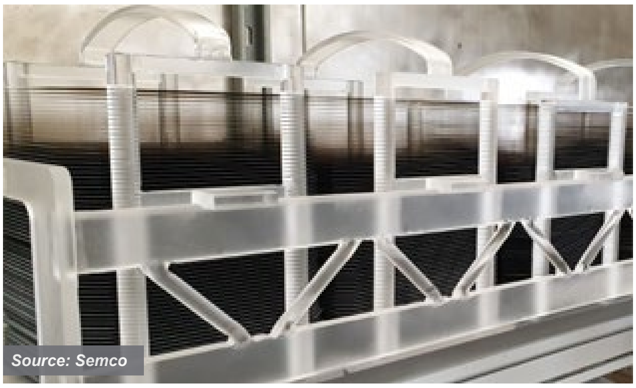
there are several equipment vendors offering tools for this process. The process, however, is quite important in that the emitter profile also influences the TOPCon cell performance, as mentioned above. Boron diffusion is typically carried out in tube furnaces at low pressure, and almost every leading furnace supplier has such a product platform on offer. The tool setup for boron diffusion, while more or less the same as for phosphorus diffusion, requires considerable optimization. It is typically accomplished at a higher temperature - above 1,000°C - and requires higher cycle times of 150 minutes compared to 102 minutes with phosphorus diffusion, as indicated by S.C New Energy, that results in lower throughput.

There is also a difference among the boron diffusion furnaces, i.e., the choice of precursor, and boron tribromide is the most extensively used. This precursor traditionally has one problem — the byproduct of the process acts as a glue to quartz, which may reduce uptime. However, with process optimization and improvements in reactor design, precursor consumption can be reduced considerably to a level where downtime is not a big concern anymore.
Semco, on the other hand, uses boron trichloride as it believes that it delivers better results, as the presence of chlorine keeps the tube cleaner. It also helps in gettering. Boron trichloride is supplied in a gaseous form in bottles, eradicating the need for bubblers. BSG, with a chlorine-based precursor, is easy to remove compared to its counterpart. The flip side of using boron trichloride is its corrosive nature and the safety concerns associated with it. Despite concerns, the approach seems to have earned a few more followers.

Laplace's philosophy is akin to that of Semco's for boron diffusion. Its tools are also designed to be compatible with horizontal wafer processing, using boron trichloride as the precursor. Similar to the LPCVD tools, the boron diffusion furnaces of the Chinese company are provided with paddle supports at the time of processing so as to avoid tube deformations.

One among those, S.C New Energy, is not only offering boron trichloride as an option, but it also strongly recommends its use as the precursor. According to ITRPV, doping using boron trichloride is expected to garner a market share of 20% by this year-end and would increase gradually to 30% in the coming 10 years.

Annealing: Something that is not usually discussed as deeply, but quite important, is annealing. Although the crystallinity of deposited polysilicon varies according to the technology, more towards crystalline with LPCVD and close to amorphous with low-temperature deposition technologies such as PECVD, annealing is inevitable irrespective of the deposition technology. This step is accomplished using simple RTP tools, while the thermal treatment time varies with the technology. Using in-situ doping makes the need for annealing even more compelling — despite the dopant being evenly distributed during the process, it has to be activated. Given the low



Source: Semco

Better and cleaner: Semco has been a strong advocate of boron trichloride based diffusion process, which according to the company not only delivers better results, but also keeps the process as well as quartz boats clean.

prices of the thermal processing tools and improved processing yield with annealing, the current practice is to accomplish it in separate furnaces. However, this step can be integrated into the firing process as part of future optimization.

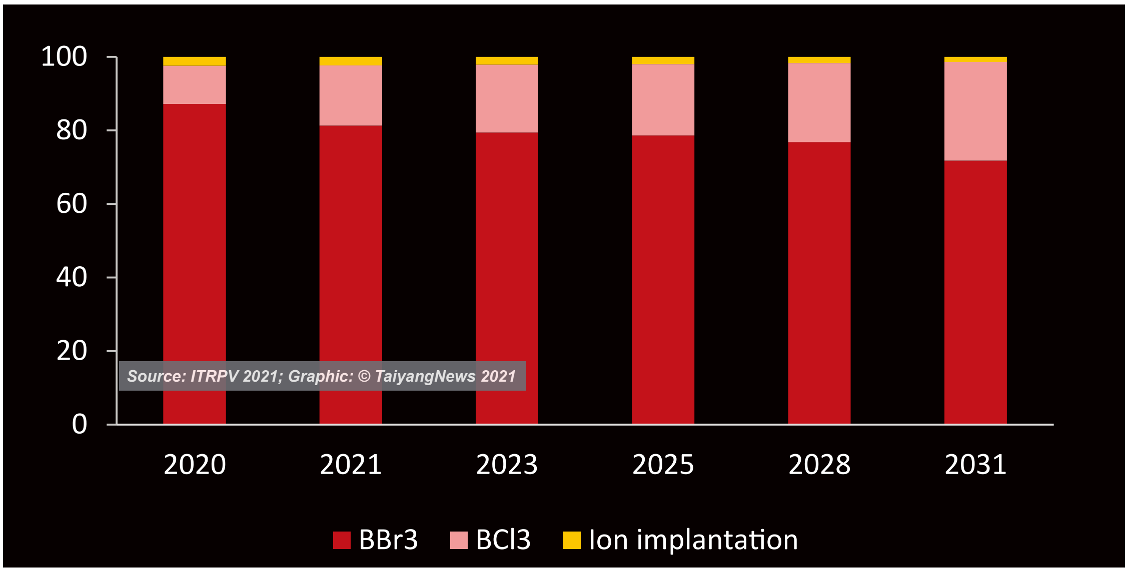
Emitter passivation: Since TOPCon is typically employed on n-type wafers, it has reverse polarity on the emitter side in contrast to PERC. Therefore, rear side passivation of the PERC structure, typically using a stack of aluminum oxide and silicon nitride, is applied on the emitter side of TOPCon cells. Nearly every aluminum oxide tool supplier offers a tool for this application, while a few have also evaluated silicon oxide and BSG in the past.

3.3 Metallization

Metallization is the tricky part in the manufacture of TOPCon cells. As with PERC, two influencers of costs are the usage of silver pastes and the deposition process itself. The difference here is that silver paste is required on both sides, almost doubling paste-related costs. The existing practice among cell makers is to use PERC silver pastes to contact the rear side of passivated contact cells. However, TOPCon requires a customized paste in order to unlock the complete performance benefits. Such pastes essentially have to possess well-controlled reactivity features with an ability to contact only the doped polysilicon film, while not hurting the underlying tunneling oxide. There is also a limitation on the front side; the silver pastes used for the emitter side of n-type cells are typically doped with aluminum, thus requiring higher firing temperatures, even compared to PERC. Since the contacts have to be co-fired, a complementary paste chemistry has to be established that can satisfy the requirement on both sides of the cells.

Most leading paste manufacturers, such as Heraeus, DKEM and Fusion, have been developing such pastes in close cooperation with TOPCon makers. Since the TOPCon technology has been under evaluation in testing and pilot lines of most manufacturers (Jolywood being an exception), the developments in pastes are client-specific. Thus, the advanced paste formulations for TOPCon are often not promoted in the open market.
DKEM is the only company to provide some insights. The company launched TOPCon specific pastes two

Different Precursors for Boron Doping



A chlorine push: While BBr3 has been the predominant choice of precursor for boron doping over decades, BCl3 is now increasingly promoted — an approach Semco has been following since the beginning.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years ago. While it is promoting two pastes each for front and rear, its DK93T is special among them. It is a rear finger forming paste and the paste platform is designed for a typical TOPCon structure of 120 to 140 nm thick polysilicon layer, which is mainstream, according to DKEM's technology and marketing vice president Kevin Nan. However, the company is ready to work with customers to optimize the formulation to be compatible with specific polysilicon layer thickness of the cell maker. "We can support the polysilicon layer thickness down to 60 nm," says Nan. The paste is also designed to be compatible with alkaline polished rear surface morphology, a new trend in the TOPCon segment in place of acidic texturing, adds Nan.

The typical paste laydown with TOPCon structure, according to Nan, is about 140 mg per cell based on the M6 wafer format, while a few paste manufacturers have also managed to push the limits to 100 mg to 120 mg. "It is tough to balance performance and reliability at this level," underscore Nan. "However, the finger widths are different for front and rear. While it is easy to attain 30 µm on the front, reaching such low finger widths with Ag-Al paste is a challenge," underscores Nan. "Nevertheless, 35 µm is achievable," he added.

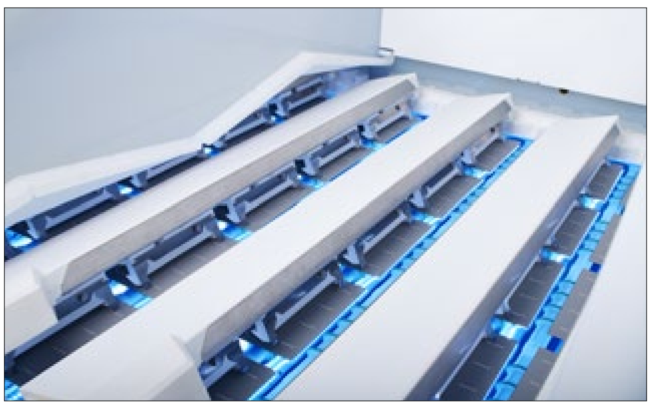
Jolywood, for example, is able to achieve finger sizes as narrow as 30 µm, while Laplace says that 100 mg paste laydown has already been realized in production for a bifacial cell requiring silver contacts on both sides. Every equipment maker and manufacturer TaiyangNews spoke to expressed that the pace of paste development has been satisfactory.

While this is the direct impact, pastes also influence the deposition process, especially the throughput. As discussed earlier, the typical thickness of a polysilicon film ranges between 80 to 150 nm, but thinner the better — the thinner the film, the shorter the deposition cycle, thereby improving the throughput of the deposition tools. While there is no limitation in terms realizing thinner films on the equipment side, it is mainly limited by compatible metallization pastes.

Plating:
Characterizing high manufacturing costs associated with metallization pastes as one of the prime hurdles for TOPCon, RENA is promoting copper plating as an alternative to screen printing. Summarizing the recent advancements associated with InCellPlate, the plating platform of RENA, Kuhnlein emphasizes that the current generation products do not need N2-annealing. Its tool follows a process flow of laser opening and the subsequent plating on both sides, and finally annealing of the contacts. The company's plating solution enables a narrow finger width with 10 µm laser opening.

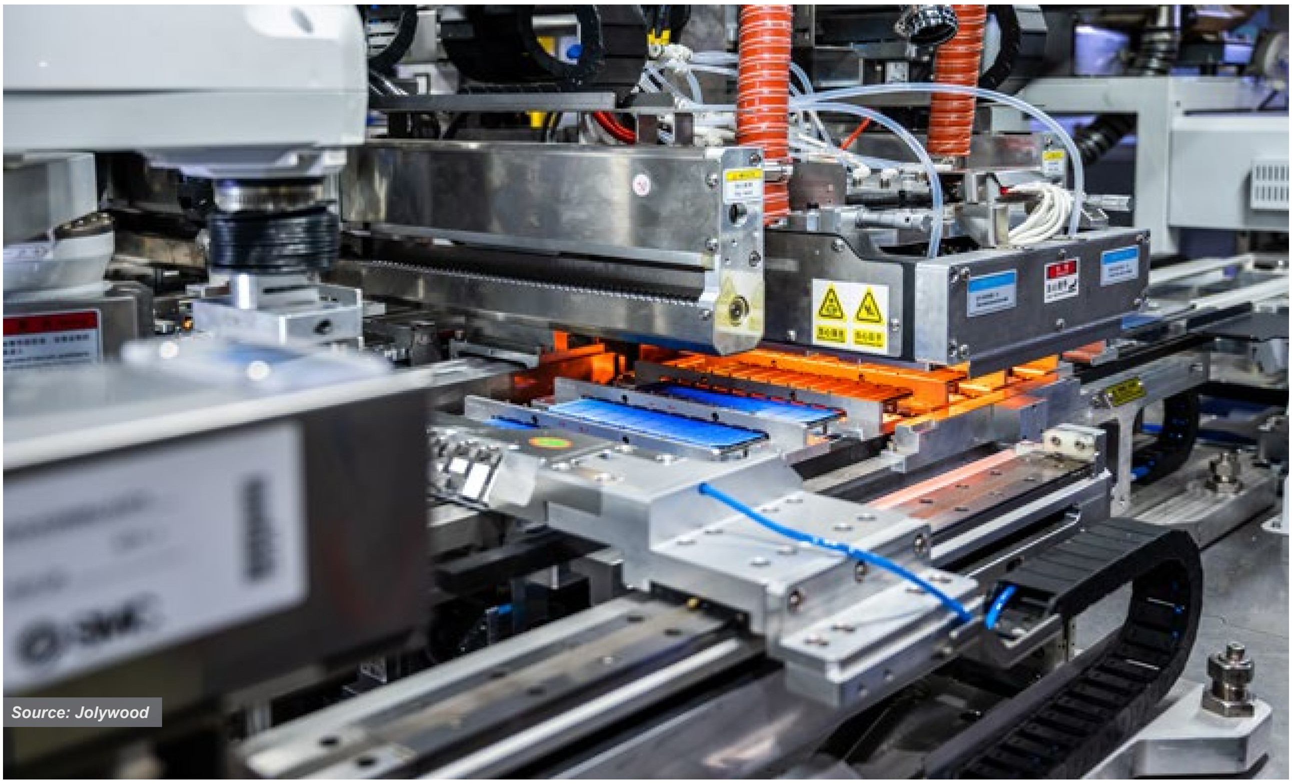
RENA has been working with JinkoSolar to develop plating-based metallization solutions. The company provided an update highlighting that they have been able to achieve an efficiency of 23.9% with JinkoSolar's HOT2.0 technology, 0.1% higher absolute efficiency over the baseline screen-printed contacts. However, the current average efficiency is at 22.6% and RENA has the roadmap in place to


Source: RENA



Savings on several fronts: RENA'S copper plating solution not only eliminates the precious metal silver from the cell's BOM, it also helps in reducing the finger thickness down to 10 µm.

increase this level to 23.5% by 2022 using copper contacts. The company further emphasizes that the damage induced by the laser and plating approach is much lower compared to fire-through silver pastes, thus a higher efficiency potential of 0.3 to 0.5%. The thin contacts formed with plating also helps in improving the bifaciality.


Source: Jolywood

Module manufacturing is pretty much the same: Unlike at the cell level, module making does not require any major changes with TOPCon technology.

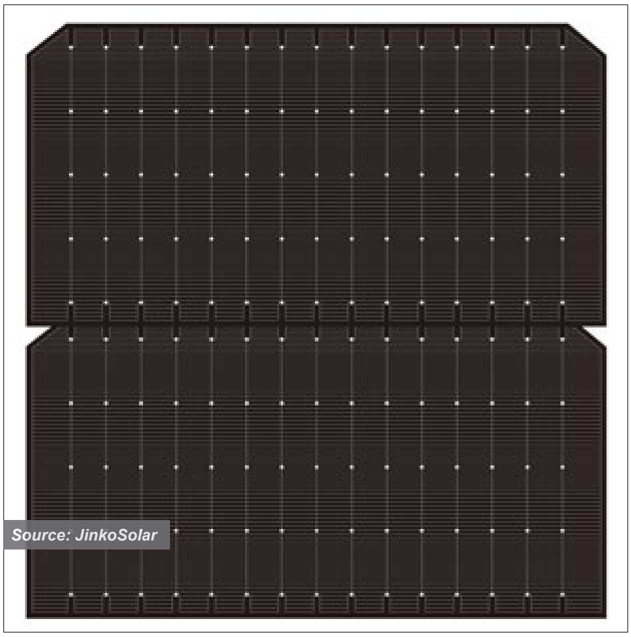
4. TOPCon performance

As discussed earlier, TOPCon comes with the fundamental advantage of high efficiency potential with the ability to considerably reduce recombination of charge carriers at the contact regions. This enables the technology to reach very high Voc exceeding 700 mV. While traditionally there were only a handful of companies that offered TOPCon products, several leading PV suppliers have joined in by unveiling TOPCon modules at the recent SNEC. This chapter summarizes the performance attributes of the technology at cell, module and system level.

4.1 Cell efficiencies

As we have discussed above, the TOPCon technology has higher theoretical efficiency potential at 28.7%, which is even higher than that of HJT's 27.5%. However, the best TOPCon efficiency reached so far has been by ISFH at 26.1%, still less than the best HJT cell efficiency of 26.63% by Kaneka. These two top figures were actually achieved by combining the IBC architecture with respective technologies. ISFH set its record by combining its proprietary POLO structure with IBC adapted to the p-type base wafer. For a double-sided contacted cell, Fraunhofer ISE announced a record 26% efficiency for its TOPCoRE cell, an architecture adopting rear junction architecture on the TOPCon structure.

The race among the mainstream PV manufacturers has actually been an interesting one, with a series of performance records announced since the end of last year. Trina Solar, one of the early adopters of the technology, held the best performance figure of 24.58% till July 2020, to be surpassed by JinkoSolar's 24.79%. It didn't take long for JinkoSolar to break its own record, hitting 24.9% in the beginning of January 2021. LONGi, a strong proponent of p-type PERC, announced in April 2021 that it broke the 25% barrier by achieving 25.09% for its 242.77 cm2 TOPCon cell technology called HPC. In June, just about 2 months later, JinkoSolar regained the spot by announcing an efficiency of 25.25%. Close, but no cigar — LONGi announced the very next day that it had achieved 25.21%, falling short by a mere 0.04%, while the average pilot run efficiency is at 24.34%. During the same time LONGi announced another a record efficiency of 25.02% for TOPCon structure on p-type substrate, which has been improved to 25.19% in less than 2 month's time. Not just setting up the record, JinkoSolar has also increased its commercial activities with TOPCon, reaching 24.15% efficiency in mass production, as indicated at the TaiyangNews virtual conference on Very High Power Solar Modules. JA Solar is yet another mainstream top tier company that is also evaluating TOPCon. The company is currently in the pilot phase with an average efficiency of above 24%.

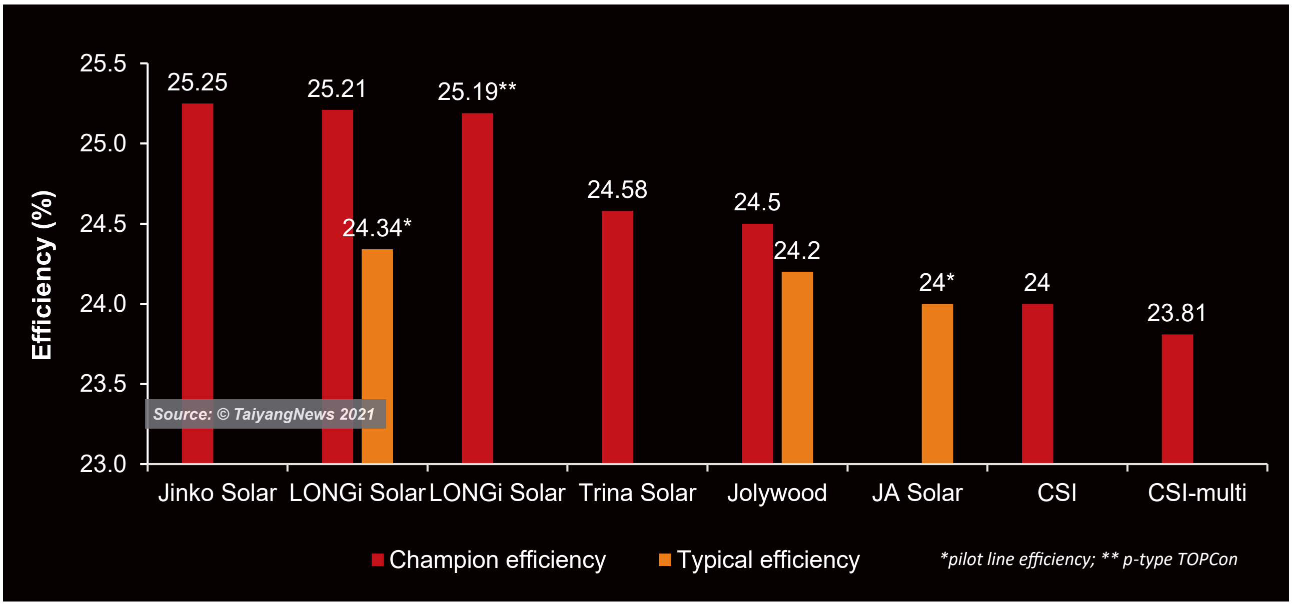


Source: JinkoSolar

From the house of champion: While there has been a race among mainstream supplier to set the highest efficiency record, currently JinkoSolar has the honor of being at the top with the best reported efficiency of 25.25%.

That said, Jolywood has been the leader when it comes to commercialization of TOPCon and perhaps the only company running a GW scale TOPCon production line (event though there are few other GW-level pilot lines). Jolywood started with n-type PERT technology and improved it from 21.5% to 22% between 2016 and 2018. In parallel, it started development activities for TOPCon in 2017 with an initial efficiency of 21.8%, which currently stands at 23.8% average in mass production. With its TOPCon 2.0 technology implemented in a pilot

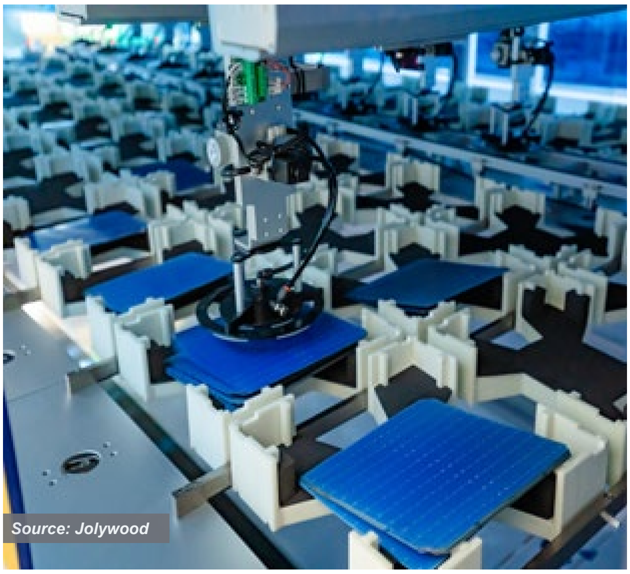
Champion & Typical TOPCon Cell Efficiencies



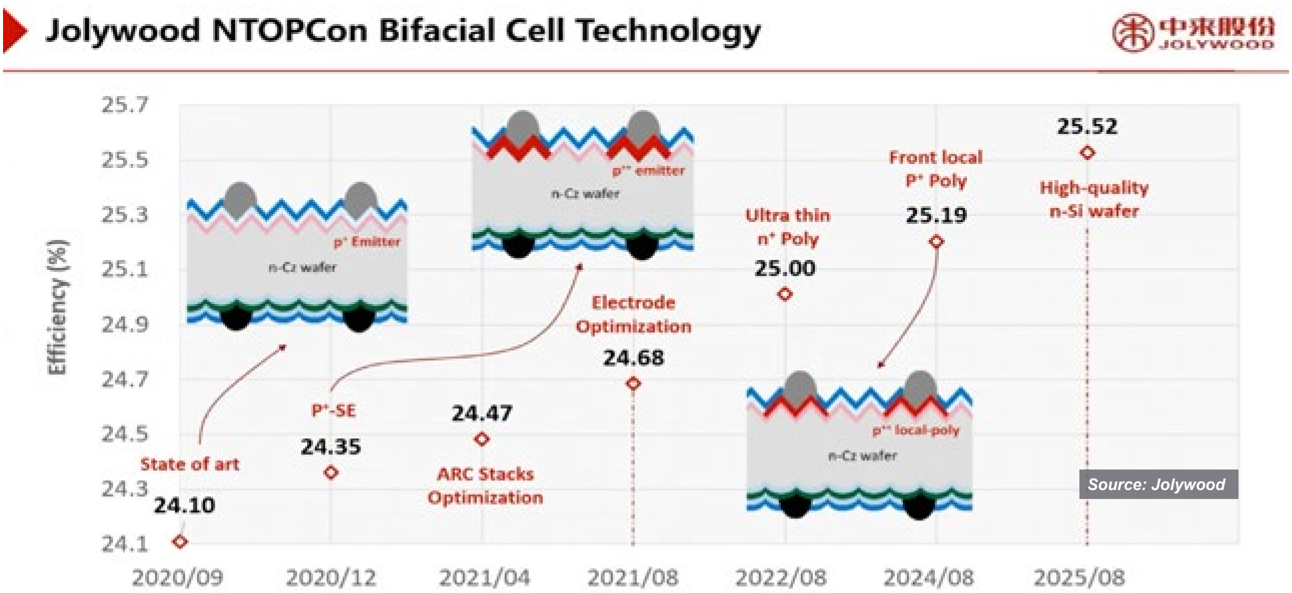
Efficiency levels: Recently, TOPCon has attracted the attention of PV cell/module manufacturers — and is now quickly reaching new heights in efficiencies.

scale, Jolywood has already achieved 24.09% average efficiency with 97% yield, while the best R&D efficiency achieved is 24.5%. Jolywood also shared its roadmap to further increase its efficiency levels at TaiyangNews High Efficiency Cell Conference. With optimization approaches such as implementing selective emitters, optimization of anti-reflective coatings and electrodes and reducing the thickness of polycrystalline silicon film, the company aims to hit 25% efficiency by second half of 2022. Adapting the TOPCon structure also on the emitter side, but selectively under the contact with local polycrystalline, the company is expected to gain about 0.2% absolute, which is expected to be accomplished in 2024. Employing high quality wafers is expected to bring the last leg of the improvement, reaching 25.52% by 2025, according to Jolywood. The company is also planning to progress to a next generation cell technology, such as the tandem structure, also based on TOPCon, which is used as the base and perovskite on top, to break the 26% barrier for a crystalline silicon cell.

Another very important development within the TOPCon segment besides efficiency is the scaling up of the technology to larger wafers. The key players have already implemented the technology on M10 wafers and very recently, at SNEC, a few companies even exhibited and launched modules based on G12 wafers.



Commercialization leader: Jolywood has led the way in commercializing TOPCon; it is not only the first to run a GW-scale production facility, but the finished cells also have close to 24% average efficiency.



Development roadmap: Jolywood has shared its development plans at TaiyangNews conferences to increase the efficiency of its TOPCon technology to 25.5% by 2025.

4.2 Power Output of TOPCon Modules

Commercial TOPCon module offerings are far and few in between, since most of the companies were only running testing lines until now. The handful that did offer were the traditional TOPCon manufacturers like LG and Jolywood. In 2019, Trina Solar started offering TOPCon modules, joined recently by SPIC. However, at SNEC 2021, there was a slew of high power TOPCon module introductions by a number of companies (see graph below).

Jolywood offers a wide range of TOPCon modules, with 4 products at the top of its promotion list. These modules fundamentally differ in terms of wafer size – either 182 mm or 210 mm – and number of cells, with 2 models in each wafer format and a power rating in the range of 415 W to 700 W. The G12 wafer-based modules are interconnected using 12 busbars, while the smaller M10 configuration uses 11 busbars, with half cells being a common attribute across the range. The top of the range, called Niwa Max, is a 700 W module integrated with 66 G12 cells and a module efficiency of 22.53%. A smaller version built with 60 cells has a power label of 640 W and a slightly higher efficiency of 22.61%. The M10 product range of the company has 2 modules – 72 and 54 cells – with rated power of 560 W and 415 W, respectively.

Trina Solar, being a strong supporter of the G12 format and one of the companies that started evaluating TOPCon technology very early, has implemented the technology on the 210 mm wafer format and launched a 700 W module at the SNEC 2021.

Ready for primetime: JinkoSolar has stepped up its activities in the TOPCon area; the company has launched its Tiger Neo globally with a power rating of 620 W.

The n-type variant of JinkoSolar's Tiger Pro module series, launched at SNEC 2020, now tops the list of products promoted at this year's show. The product series was also presented at the TaiyangNews virtual conference on Very High Power Solar Modules. JinkoSolar calls its technology HOT 2.0. At the module level, the TOPCon variant of Tiger Pro called Tiger Neo closely follows the design aspects of its PERC counterpart – bifacial, half cell, MBB and Tiling Ribbon – but with slight modifications. One such change is that the MBB layout of modules uses 10 busbars (wires) instead of 9. After careful evaluation, JinkoSolar found that a wire thickness of 0.35 mm is optimal for the 10-bubsar layout. However, the design template of its proprietary Tiling Ribbon for cell interconnection remains the same. Here, the 0.35 mm round wires used for interconnection in MBB designs are pressed flat exactly where they would bend in order to connect the top of the next cell. Instead of placing the cells side by side, the silicon slices slightly overlap at the edges. The module also uses a specially structured encapsulation that fills the overlapped region, providing extra cushion to avoid mechanical stress during the lamination process. The module has a power rating of 625 W and a high efficiency of 22.86%. However, JinkoSolar has launched a commercial version of the model with slightly altered specifications. The best mass-produced Tiger Neo module has a power rating of 615 W and 22% efficiency.

As hinted during the TaiyangNews event, LONGi Solar and JA Solar presented their first TOPCon modules at SNEC. LONGi's module, called Hi-MO N, is based on M10 with a module power of 570 W and 22.3% using 72 cells. JA Solar's product, also based on the same format, is a 620 W module based on 78 cells. Recently the company launched a module based on G12 format with a power rating of 690 W and 22.2% efficiency. Other notable TOPCon product presentations at SNEC and their respective rated powers are as follows:

- Tongwei — 695 W
- Suntech — 620 W
- Das Solar — 560 W
- GCL — 475 W
- Astronergy — 470 W

Even Risen, a longtime and very outspoken supporter of HJT, has launched a module based on blended technology – combining TOPCon and HJT. According to the limited information available, the technology uses TOPCon structure on the rear. This approach is expected to increase the Voc and current density compared to the traditional HJT structure. This module series called as NewT@N built on G12 wafer format has a rated power of 700 W and 22.9% efficiency.

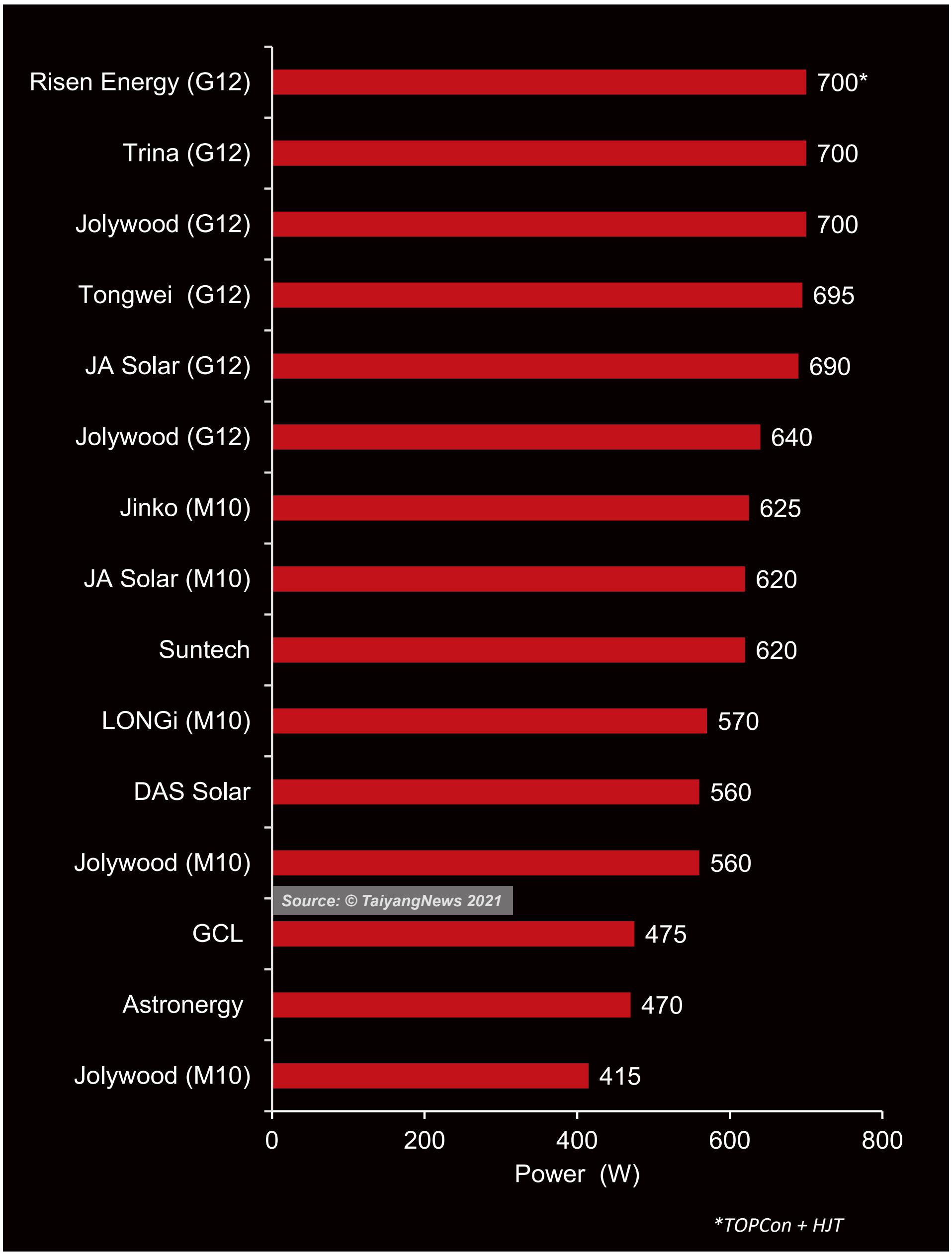
Source: JA Solar

JA Solar is another leading PERC player that is also evaluating TOPCon technology seriously; it launched a 620 W product at this year's SNEC.

4.3 TOPCon at System Level

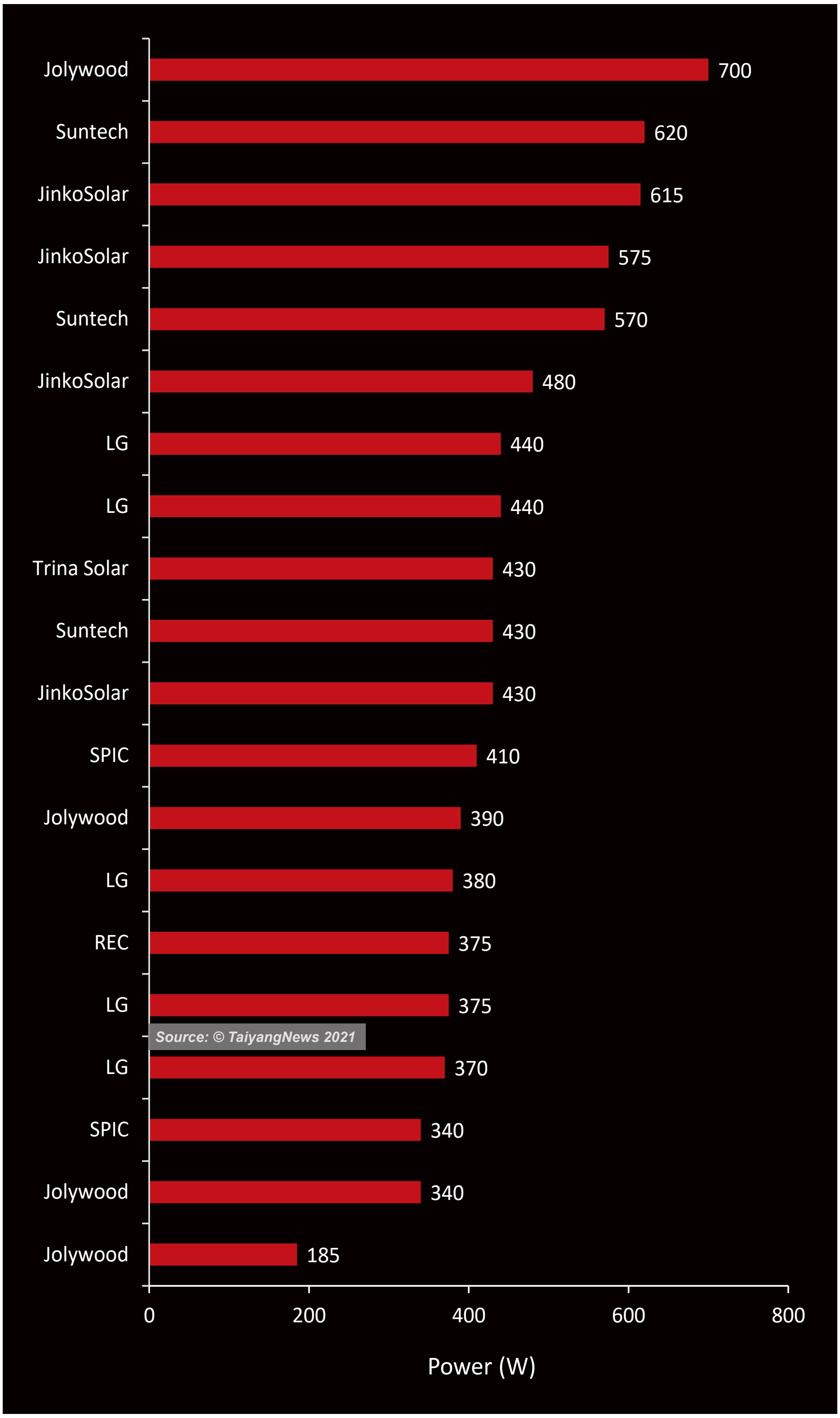
TOPCon not only results in higher efficiency at the cell level, and higher module power as a consequence, but the technology also performs well outdoors in real-world operating conditions. Its key benefit over the incumbent PERC technology is that the current industrial practice is to implement the technology on n-type based wafers. This fact is entitlement enough for it to be free from light induced degradation (LID). Jolywood's R&D director Jia Chen presented the company's internal as well as third-party testing data at TaiyangNews Very High Power Modules event. The in-house testing data showed that the TOPCon modules, when subjected to testing conditions of LID, actually showed a slight power increase. The results of testing TOPCon modules at

Power rating of different TOPCon modules launched at SNEC



New interest in TOPCon: If new products presentations at trade fairs are any indication of higher interest, SNEC 2021 saw several module makers introduce TOPCon based module products. When and how much will be produced, is another question.

Commercially Available TOPCon Solar Modules



Commercial crop: Only a handful of module manufacturers are supplying TOPCon modules commercially, and Jolywood is leading the pack with a wide variety of products on offer.

Fraunhofer ISE are very close to Jolywood's internal testing. Whereas the PERC modules suffered a power loss of up to 5% in LID testing sequence, Jolywood's products showed a slight power gain of 0.5%. As for LeTID, another important degradation mechanism, Liu Zhifeng, VP technology at Jolywood, presented another set of test results at TaiyangNews High Efficiency event.

According to the quoted test results from TUV, PERC modules typically suffer a degradation of 2 to 3% due to LeTID, n-PERT technology was unaffected by the phenomenon, whereas for TOPCon modules the power increased slightly by 1%. Jolywood also deeply investigated this degradation phenomenon in its own lab and found that LeTID test resulted in a slight increase in power in most of the test cases. Zhifeng explained three phenomena in detail for the lower degradation (if not for power gain).

- The solubility of hydrogen in n-type wafer is significantly lower than in p-type. That means less hydrogen would in-diffuse into the n-type silicon bulk than p-type silicon during the firing. The lesser the hydrogen, lower the formation of H-P (N-Si) bond formation, thus lower the degradation.

- The binding energy of a P-H pair in n-type silicon (0.41 eV) is much lower than binding energy between a B-H pair in p-type silicon (0.5 eV). Thus, in annealing conditions, the process is quicker, so is the recovery.

- The diffusivity of hydrogen in n-type silicon is often measured to be orders of magnitude higher than the diffusivity of hydrogen p-type silicon. Thus, hydrogen effusion is more rapid for n-type, which may lead to accelerated recovery.

Betting on this low degradation, both Jolywood and JinkoSolar are guaranteeing a first-year degradation limit of 1% and the spec for annual degradation is 0.4%, while the same specs for PERC products are 1.5% to 2% and 0.45% to 0.55%, respectively.

Low temperature coefficient is yet another advantage of the TOPCon cell architecture compared to p-PERC. While Jolywood puts 0.32%/°C as the spec for the temperature coefficient of power for its TOPCon modules, the PERC modules from leading suppliers are rated with 0.34 or 0.35%/°C. According to Jolywood's Jia, every 0.05%/°C decrease in temperature coefficient has the potential to reduce the LCOE by 0.9% to 1.3%. Counting on these benefits, Jolywood is primarily promoting its products to arid regions such as the Middle East, where the temperature as well as the ground albedo is high – the latter being beneficial for bifacial.

Bifaciality is an important aspect of the TOPCon structure. On one hand, the structure suffers from undesired absorption of light in the doped polysilicon layers, leading to lower bifaciality compared to its peer n-type technologies such as n-PERT or HJT. One way to improve the bifaciality is to reduce the thickness of the polysilicon layer. However, Chen emphasizes that film thickness is just one of several factors influencing bifaciality including shading due to metallization, rear surface morphology (textured or polished), rear passivation quality and finally the wafer quality. Of course, reducing the layer thickness not only improves the bifaciality, but also the throughput of the deposition tools, ultimately helping to reduce costs. While Chen would not disclose the exact film specifications, "about 100 nm" is the ballpark figure he says. On the other hand, the bifaciality of commercial TOPCon modules is certainly above the mark; JinkoSolar boasts 85% bifaciality with its TOPCon modules. Even Jolywood's 80% is higher than the 70% spec for most of the PERC modules out there. According to Jia, each 10% increment in bifaciality reduces LCOE by 0.7% to 1.1%.

When it comes to its applications, the promise of high efficiency that comes with TOPCon led its early adopters such as LG to promote their products mainly for rooftop applications. Given the space constraints and high energy demand per available area, this application commands a price premium over C&I and utility counterparts. In contrast, while Jolywood also has products for residential, its core focus is utility. According to Jia, the TOPCon products of this company, in addition to being part of several installations under China's "Top Runner" scheme focused on technology, were also used in several utility projects in different parts of the world.

He further emphasized that the company's products are best suited to hot regions such as the Middle East, to which the company has shipped modules worth about 900 MW so far, while its total n-type module shipments totaled 4 GW by end of 2020. Even JinkoSolar's latest TOPCon products were designed keeping the demands of large-scale power plants in view, i.e., larger modules and high power.

Source: Jolywood

Addressing power plant market: Unlike most of the early adopters of TOPCon that have mainly focused on the premium rooftop segment, Jolywood is primarily concentrating on the utility market as shown in this map.

5. Commercialization & Production of TOPCon

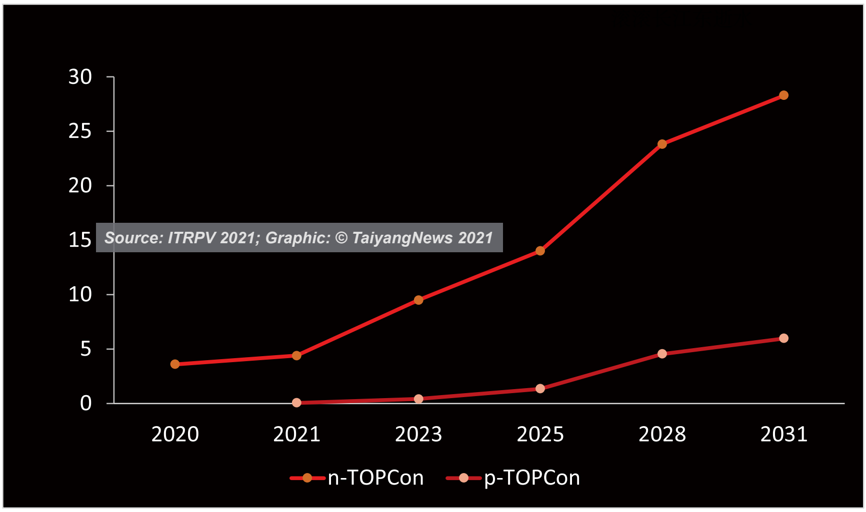
It is encouraging to see several companies launch TOPCon products. And while PERC remains the main and key product for most of these companies, their production plans for TOPCon are more driven by market demand. As mentioned earlier, most leading companies have pilot/test lines where they are in the process of evaluating the technology. And only a handful of companies have entered commercial production of TOPCon products as of the time of this report. Jolywood is the leader in TOPCon with a production capacity of 2.1 GW for cells and 3 GW for modules, and recently announced plans to extend it further by 16 GW in two phases. Split into 8 GW each, the first phase is expected to take about 2 years and a year thereafter for the second.

As for the other major players, TOPCon is just a fraction of their existing cell capacities, but a few worthy mentions nonetheless. JinkoSolar said at the TaiyangNews event that n-type cells currently comprise 800 MW of its existing capacity. Suntech is cooperating with Leadmicro to build a 2 GW factory. While not officially confirmed, LONGi has installed a GW scale production facility for TOPCon. In March, Taiwanese solar cell and module producer United Renewable Energy Corp. (URE) was reported to have plans to launch small-volume mass production of TOPCon cells in 2021. Solar cell manufacturer Aiko Solar has also decided to add n-type to its product portfolio with a total capacity of 8.5 GW, as announced at SNEC 2021. However, it is not known whether this is for TOPCon or HJT.

When PERC reaches its limit, and it surely will soon, after it got to higher commercial efficiency levels most experts anticipated, the big time for TOPCon is likely to come.

Currently, teething issues with passivated contacts are addressed, but then most of the existing PERC capacity will need to be upgraded – and the natural progression is passivated contacts cells. During the panel discussion at the TaiyangNews High Efficiency conference, it was estimated that the TOPCon capacity is expected to exceed at least 10 GW by 2022. However, with several companies now having ventured into the technology, hitting a level of 15 GW by year-end doesn't seem too far-fetched. ITRPV estimates that this technology as a whole would progressively increase its market share from a mere 4% in 2021 to little less than 35% in the next 10 years. This forecast, however, is for n-type and p-type combined. As things stand, n-type will continue to be the bulk material of choice, p-type's share is too small to be even noticed and is only expected to start making a mark by 2025.

TOPCon Market Share – ITRPV



Also for p-type: While TOPCon in today's context is synonymous with n-type, ITRPV also expects the p-type variant of this high efficiency cell technology to appear starting in 2023.

6. Costs

Reducing costs is going to be the key for TOPCon to be competitive at scale. The technology certainly requires higher CapEx compared to PERC. Again, as discussed above, even with all the efforts put into simplifying the process through new deposition technologies, the number of steps could only match that of PERC. This still translates into higher capital expenditure, as the steps involved are more complex in and of themselves. A few examples would be boron diffusion for emitter formation, rear passivation stack and the consequent wet-chemical treatment steps. This complexity makes the production tools that much more expensive. And given that it is still a budding technology, TOPCon is yet to tap economies of scale. A 1 GW production line of TOPCon demands about 200 to 250 million RMB in CapEx, which is about 40 to 50 million RMB higher than that of a PERC line of similar capacity.

According to several articles published in Chinese solar media, manufacturing costs are also about 20% higher than PERC. In absolute numbers, the non-silicon costs associated with TOPCon are 0.05 to 0.09 RMB/W over PERC. The fact that TOPCon employs n-type wafers itself makes it slightly more expensive, and the silver pastes applied on both sides add to the burden, let alone higher depreciation costs due to higher CapEx. However, with the measures already put in place to reduce paste consumption, several experts opine that equipment costs are going to come down further quickly. Driven by high-volume production efficiencies and, most importantly, an enhanced efficiency delta between PERC and TOPCon, the technology is sure to make a mark for itself soon.

7. Challenges & Opportunities

Like any advanced cell architecture, TOPCon is not without its limitations. High CapEx and OpEx are the obvious main challenges as discussed in the section above.

Primarily on the rear: One key limitation of TOPCon is that its application is currently limited to the rear side of a cell, mainly due to undesired sunlight absorption in the doped polysilicon layers. Theoretically, to make TOPCon work on the emitter side requires a local polycrystalline structure under the contact. This is something that is not feasible cost-wise in high volume manufacturing, at least as of now.

Silver on both sides: Again, as discussed in the costs section, silver pastes are an expensive component of TOPCon. However, as the market grows, the industry is sure to put in the time and effort required to reduce paste consumption and, in turn, costs.

Low compatibility with p-type: Today, passivated contacts is somewhat synonymous with n-type. And as p-type is the de facto mainstream, there is still some reluctance on the part of manufacturers given the payoff isn't as lucrative, at least as of now.

PERC impresses: As a technology, PERC has been growing in leaps and bounds, as has been the industry's focus on it. This is the biggest hurdle for any new technology, and passivated contacts is no exception. The efficiency delta between TOPCon and PERC cells isn't huge, for one thing. For example, efficiency and power figures of 21.61% and 560 W for a TOPCon module are not much ahead of an equivalent PERC module with respective values of 21.3% and 550 W. And even with single side deposition, TOPCon involves more steps compared to PERC, adding to costs. The rule of thumb was that as long as the gap is much less than 1% efficiency, manufacturers will not switch from PERC to TOPCon.

However, the latest generation TOPCon products have showed some good progress. The latest G12 based J-TOPCon 2.0 module from Jolywood has a rated power of 700 W and 22.23% efficiency. A comparable PERC module, also built with 66-G12 cells, delivers 670 W of power and 21.6% efficiency. TOPCon certainly looks attractive at this level, but if and only if PERC development stagnates at this level. However, developments on the PERC side cannot be totally counted out.

Close to PERC: On the other hand, TOPCon is very similar to PERC both in terms of structure as well as the manufacturing process – something that could play in its favor. While it does require a few additional production tools, most components of a PERC line can still be used. The overall process is high temperature compatible; and while it still requires some optimization, the wheel need not be reinvented in terms of important process consumables such as metallization pastes. The module manufacturing can also remain the same as that of the standard, and the technology is equally compatible with all advanced module concepts. The close resemblance to PERC has also made it easy to scale up to larger wafers. All in all, there is no denying that TOPCon requires an extra effort at the cell level, but it does pay off with better performance in the end.

Ready to partner for upgrades: An important opportunity for TOPCon is fusing the structure with IBC in the production setting. At the R&D level, ISFH has already demonstrated record level performance with such a cell structure. TOPCon can also serve as a bottom cell of a tandem structure with perovskites on top.

8. Conclusions

The breadth of TOPCon modules showcased at the 2021 SNEC trade show was quite a surprise – several of the leading module manufacturers presented products at their booth. Panel efficiencies across the board exceeded 22%, the best product touched 22.9%. And when looking at power ratings, 3 companies – Jolywood, Trina and Risen – displayed 700 W panels. Impressive!

Indeed, TOPCon has been considered a candidate to succeed incumbent PERC for quite some time. But its direct competitor HJT lies ahead with higher efficiencies for commercial products. And PERC has fared much better than most experts expected when it took over from Al-BSF a few years ago. Not only have PERC cell production efficiencies reached very high levels (now close to 23%), the dramatic improvements in module design based on very large wafers have resulted in panel performance levels hardly anybody would have believed to come true using PERC.

However, the air is getting very thin for further economically viable improvements of PERC modules, while the cost pressure is increasing in times of raw material shortages and resulting price hikes. Project developers need much lower cost modules – and every year much more. The answer is higher efficient solar cells, such as TOPCon.

Its resemblance to PERC in terms of structure as well as manufacturing are undeniable advantages, one up over its key contender HJT, which requires a very different production line design. The similarity extends to scaling up to larger wafers.

But the early hopes in TOPCon have yet to materialize. While from the perspective of former n-PERT technology supporters, TOPCon was considered the light at the end of a tunnel, it attracted in the beginning only few large players, who seemed to lose interest quickly, or at least didn't make the desired progress. Despite being touted as a natural upgrade from PERC, TOPCon owns a negligible market share among production technologies. Jolywood is the only commercial TOPCon cell/module manufacturer of note, though in the low, single digit GW-scale.

We shouldn't forget, it wasn't too long ago that PERC faced the same hurdles. Today, TOPCon is to PERC what PERC was to BSF in the past. It brings the same performance advantages and a similar number of additional process steps.

A key issue in TOPCon cell production has been LPCVD, given its inherent limitation of wraparound, apart from the higher number of process steps and associated costs, and low process yields. The efficiency gap that would justify the investment to upgrade from PERC is still too small.

But things are changing. Alternative technologies are becoming available, such as tweaked tool designs for LPCVD that can alleviate the wraparound issue. New deposition technologies are coming into play with the promise of reducing the total number of process steps. When talking to equipment suppliers, they do show new optimism for TOPCon. If new innovative tool platforms will be introduced and the process sequence optimized, the 15- 20% cost gap between TOPCon and PERC will likely narrow. This should be helped through lower tool and material prices as a result of competition between equipment companies, which increasingly work on TOPCon technology.

The many TOPCon modules on display at SNEC were revealing indeed. Notably, leading module manufacturers are increasingly talking about their TOPCon product developments at conferences. At the same time, pilot lines are getting more and growing bigger, and starting to churn out the first commercial products.

Still, it's hard to say when TOPCon will see its real breakthrough, especially since we have seen a strong PERC Capex phase in the last two years. While TOPCon focused company Jolywood just announced to expand its production capacity strongly close to 20 GW, the big players will move away from PERC only gradually. Finally, we have to simply wait and see who of the TOP companies surprises us most, opting for TOPCon over HJT.

5. Interview – Jia Chen, Jolywood

The world's largest solar trade fair SNEC 2021 showed a spurt in n-type TOPCon technology. Jolywood, the long-time TOPCon advocate as well as several leading suppliers known for their gigantic p-PERC capacities unveiled new TOPCon products. Jolywood struck a chord regarding several topics — technology progress and production expansion to a 2-digit GW level at 3 production sites in China. TaiyangNews talked to Jia Chen, Deputy General Manager of Jolywood, about the current status of its TOPCon manufacturing, its future plans and technology insights.

JIA CHEN, DEPUTY GENERAL MANAGER, JOLYWOOD

Jia Chen is the Deputy General Manager for R&D and Application at Jolywood. With a strong academic and research background including obtaining a Ph.D. degree and a position at IMEC in Belgium, one of the leading European research centers, Chen is now overlooking the R&D activities at Jolywood.

TaiyangNews: **Jolywood is somewhat special in two aspects – a leading backsheet supplier expanding into cell manufacturing; and then when the PV world was focusing on p-type, especially PERC, Jolywood was among the handful of companies to pursue the path of n-type. So first, why the decision as a world-leading backsheet manufacturer to expand into cell/module manufacturing?**

Jia Chen: *At Jolywood, improving PV technology is front and center in our constant endeavour to help the industry further reduce the levelized cost of energy. When we started, the PV industry was really booming and is still a rapidly progressing industry. We have seen the pace of installations pick up rapidly across the globe, and we strongly believe that trend will continue for the foreseeable future. At Jolywood, our belief has always been that the technology is the engine for this improvement. And this improvement in technology comes on the back of improvements in all the materials, such as backsheets, ribbons, etc.*

Also, cell technology is one of the key factors that can push the levelized costs of energy of PV technology lower so that more and more people around the world can enjoy this renewable and green energy. For this reason, our founder decided to focus on the cell manufacturing side, especially the high efficiency n-type. As you can see, Jolywood is not making any PERC cells, but has been pushing on n-type cells over the past 5 years, no matter how difficult it was.

TaiyangNews: **Can you walk us through your thought process behind moving into n-type – both IBC and n-PERT, rather than jump onto the p-type PERC bandwagon?**

Jia Chen: *Yes. When Jolywood chose the path of n-type in 2016, it was not as popular it is now. Our founder's in-depth research showed that n-type solar cells have the potential to reach much higher efficiency. Firstly, the material itself is much superior compared to the incumbent p-type, meaning that the modules can deliver much higher power and, as a result, reduced levelized cost of energy. Additionally, n-type holds the advantage over p-type in almost every aspect, be it bifaciality, degradation or reliability. So we're now seeing our conviction in n-type as the way of the future coming true.*

Having said that, I must also emphasize that the journey has not been an easy one. When we started, benefits of n-type were hardly acknowledged. A lot of our customers did not believe that modules can generate electricity from the rear side, let alone the benefits such as low temperature coefficient and no degradation. Multiple departments of the company, especially the marketing, sales and technical teams, had to work very hard to put the data in front of the *customers to convince them on how a solar project can benefit from these advantages.*

TaiyangNews: What is your current cell/module production capacity for TOPCon / IBC – and what are your expansion plans?

Jia Chen: *The current TOPCon production capacity of Jolywood is 2.1 GW. We are planning to add 1.5 GW in Taizhou, Jiangsu Province and 16 GW in Shanxi Province.*

TaiyangNews: When did you decide to upgrade from PERT to TOPCon – and why?

Jia Chen: *It was sometime in 2018, and there were a couple of reasons, the first being that PERT is very similar to p-PERC both in terms of cell efficiency and potential. We know that making n-type cells involves higher costs. So if the cell efficiency is comparable, and the cost is higher, there's no advantage for us as well as for our customers. It meant that we had to upgrade our technology. As part of this, we did a very detailed loss analysis of our cell architecture. The key losses for our n-PERT cells were at the contact region or at metallization. To solve this problem, we decided to improve the contact region. It was a time when TOPCon was very hot in academia and was exactly what we had been looking for, as TOPCon is about passivating contacts. On top, we just need one additional step for upgrading n-PERT to TOPCon, implying the investment costs are also low, while the efficiency potential is huge. So going to TOPCon was a no- brainer.*

TaiyangNews: Jolywood is currently leading the industry in terms of TOPCon capacity and experience. What are your most important learnings during this journey?

Jia Chen: *As I mentioned earlier, it hasn't been easy. It is always difficult to bring a new technology to commercial production, and TOPCon is actually very specific. We had to establish the entire supply chain by ourselves, be it equipment, materials or other process consumables. TOPCon industrialization started only 3 or 4 years ago – that too with Jolywood and few others in the lead. This means that the key mass production knowhow was not available across the industry. So we had to connect the dots one after the other and were the first to make all this effort on how to integrate different processing tools and materials. And yes, we are very proud of the rich experience we've gained during this rather tough journey.*

TaiyangNews: A few other companies have also tried the TOPCon approach but were not able to get into high volume production or have given up altogether. What do you think went wrong with the others? And how has Jolywood managed to overcome these issues?

Jia Chen: *I don't think anything went wrong with them. Companies suspend or delay a project for different reasons. I can think of a few: different operating environments, capacity driven strategies; for example, companies might have high PERC capacities, a few would like to spend more time in evaluating the technology and wait till the technology is mature. So it all depends on the situation – the financial situation, the capacity, the beliefs or the strategies of a company. In my opinion, no company has failed so far, but rather have a different strategy and pace to realize the benefits of TOPCon technology.*

As for Jolywood, we have always been solely focusing on TOPCon and making it better and better. TOPCon is our bread and butter, and we have had to push ourselves hard to be where we are and to go further, gaining knowledge and expertise in the process.

TaiyangNews: From your experience, what are the 3 key features that will determine the success of TOPCon technology?

Jia Chen: *First of all, it is the efficiency gap between PERC and TOPCon. Currently, the efficiency delta between these two technologies is 1% to 2% in the lab setting. And recently, a lot of companies including Jolywood have demonstrated efficiencies above 25% in the lab. It shows that adding one step of putting tunnelling oxide and polysilicon layer can improve the cell efficiency and increase the module power. And with more and more efforts, we strongly believe that the non-silicon costs for TOPCon will be comparable to those of PERC.*

Next would be the other factors impacting the levelized cost of energy. To offer TOPCon in a *product form, we have had to put ourselves in the shoes of a project developer. Because it is very important for the customer how much power the module can generate in real-world conditions. The nameplate power is just indicative as the power is measured at STC, but the modules in the field operate at around 75°C. So a low temperature coefficient proves very advantageous here. Another important aspect is the bifacial feature of a cell technology, where TOPCon certainly scores higher than PERC. The customer must be educated on such advantages of TOPCon that can help reduce the levelized cost of energy with more and more relative data.*

And finally there is a need for more companies to join and cooperate for the development of TOPCon technology. It's boring when you're alone at a party. At Jolywood, we've always been vocal in inviting more people to join us on this TOPCon journey, all the while sharing our learnings to encourage others. We also appreciate full cooperation of our partners – equipment and material suppliers – without which TOPCon would have not reached where it is today. TOPCon requires different parts of the industry, value and supply chains to work together to accelerate the progress.

TaiyangNews: What are the main challenges with the technology today? What do you think will be the key challenges in 5 years?

Jia Chen: *From a technology point of view, currently the TOPCon process flow is quite complex. You cannot use a very complex processing flow-based technology to compete with something very straightforward and lean. We, at Jolywood, have been working on this technology for the last 5 years and we have suffered a lot, especially from production issues. One of the key issues in production is that, given the lengthy process flow, we had a lot of yield issues, which we have been trying to solve over time. That's why we have been focusing our efforts in shortening the process flow to improve the yield and reduce costs. For example, last year, we announced Jolywood's J-TOPCon 2.0 with our POPAID technology, which focuses more on shortening the process flow than increasing the yield. It is quite different compared to other companies that are mostly working on pushing the lab efficiencies higher. However, at Jolywood, most of the projects even at the R&D level are aimed at shortening the process flow, solving the yield issues and stabilizing the process. What we have achieved is quite commendable, but I think there is still room for improvement; we must further shorten the process flow or at least make the processing window wider, so that when TOPCon ramps up to a 10 or 20 GW level there are less issues in the production line.*

The second factor from a technology point of view is that silver consumption for TOPCon is still higher compared to PERC. Our target is to make costs comparable to PERC; thus, we need to bring silver consumption on par with PERC. And to do so, we need to work closely with paste suppliers. At the same time, we also have to optimize our process to reduce silver consumption. When this happens, costs for TOPCon would be automatically very similar to those of PERC.

TaiyangNews: How long will it take before we see some of the global cell/module leaders follow you, transforming larger PERC capacities into TOPCon?

Jia Chen: *I suppose it is already happening. A lot of mainstream tier-one companies with huge capacities have announced plans to develop TOPCon not just at an R&D level, but serious plans for production. There have also been some announcements of upgrading PERC lines to TOPCon. Overall, the situation is more optimistic compared to last year and I believe more and more companies will soon join the TOPCon party.*

TaiyangNews: Are you happy with the current supply chain for TOPCon – production equipment, deposition technologies and metallization pastes?

Jia Chen: *Firstly, I am very thankful to all the suppliers who are currently working on TOPCon, because the segment is quite small compared to PERC and the required R&D effort is high. I can imagine that the revenue they are generating from the TOPCon stream is not very profitable for them, which is why I am very grateful to all those who are active in this field.*

Having said that, am I happy with the current supply? The answer is unfortunately not completely. There is *a lot of scope. Paste is one example. As I mentioned earlier, paste consumption is still high. The losses incurred in the contacts region are still high, which has an effect on efficiency. Paste companies have to improve contact formation and reduce consumption. Boron diffusion is another process that needs optimization, which is a lengthy process involving high Capex and OpEx.*

TaiyangNews: What do you think will be the global production capacity of TOPCon by end of this year, end of 2022 – and in 5 years?

Jia Chen: *At the end of this year, we should have 5 to 10 GW of TOPCon capacity globally. Not only are other companies planning to ramp up their capacities, Jolywood alone will contribute a lot to this. As for next year, it really depends on how successful the other companies are with their plans. When the mainstream companies are successful, a lot will follow them. Then TOPCon could be huge. However, it also depends on the end-customer acceptance and supply chain development. Next year, it could be anywhere between 20 and 50 GW depending on several factors, including supply chain developments. I personally believe that it will ramp up very quickly.*

TaiyangNews: Let's talk about bifaciality of the TOPCon structure. How important is bifaciality and do you see much potential for improvement?

Jia Chen: *The bifacial approach facilitates generation of electricity from the rear side, increasing the energy yield of the solar PV system. And whether it's very important or relatively important really depends on the project itself. For example, Jolywood products are very popular in the Middle East because a lot of larger projects are situated in deserts. Here, the ground is very reflective, so bifacial technology makes a lot of sense – and that is also why Jolywood's products with a bifaciality of 80% are quite famous.*

The potential for bifaciality improvement is a rather tricky question. Basically, bifaciality is the ratio of rear and front efficiency. If you just improve the front side of a cell, though there is improvement overall, it reduces the bifaciality. Similarly, improving the rear side alone makes the bifaciality higher, but that may not completely contribute to the actual improvement. As a cell maker, when we are trying to improve the cell's performance, we generally focus on the front side, because most of the light comes from the front side, thus it is very important. We want to improve the bifaciality, but not at the cost of front side efficiency.

TaiyangNews: What is your current average and champion cell efficiency?

Jia Chen: *The current average efficiency of mass production exceeds 24% and maximum mass production efficiency is at 24.5%, while the champion cell reached 25.4%.*

TaiyangNews: What do you think is the limit for the commercial average efficiency for TOPCon technology?

Jia Chen: *The average efficiency in production can reach up to 25% in 1 year or 1.5 years. Currently, the biggest losses are on the front side, which means you have to implement a selective emitter scheme or even implement a passivating contacts structure also on the front side. However, none of these are very mature at the production level, so the potential is very high for TOPCon technologies. In case of any true breakthrough on the front side, the efficiency can be improved beyond 25% in production.*

TaiyangNews: What is the main targeted application for your TOPCon modules – premium residential or even utility scale?

Jia Chen: *TOPCon, with its high efficiency and higher module power, is highly suitable for residential applications. There is no doubt about it. However, we at Jolywood believe that if costs are low enough – of course not on par with PERC but very close – with all the other additional advantages of TOPCon, it is also very competitive for utility applications. And as we have emphasized in several conferences and announcements, we have successfully implemented the technology in the utility segment.*

TaiyangNews: Can you elaborate on your TOPCon technology roadmap – and other cell technologies as you also work on IBC?

Jia Chen: *As you know, we are in production with TOPCon and IBC and are well versed with* *the advantages of these two technologies. Our main production is in TOPCon. In the future, we may consider IBC or TOPCon + IBC, we call it the TBC structure. However, for all the single junction crystalline silicon solar cells, the ultimate efficiency limit is around 29%. We believe that with tandem structures, we can further improve the efficiencies. So, in the future, we would like to stack TOPCon with other structures, maybe perovskites, which seems promising.*

TaiyangNews: Opting for TOPCon, why do you think you can beat HJT, the other potential successor for PERC?

Jia Chen: *I know that the majority of the industry views TOPCon and HJT as rivals. But we, at Jolywood, never really think of HJT as competition. I don't know whether you're aware, we are actually trying to learn from the progress of HJT. POPAID is one example. In the end, be it TOPCon or HJT, all are passivated contacts, only the approaches are different. And there are always things that followers of each technology can learn from others. Both the technologies will lead to higher efficiencies. At the end of the day, it is the investor that has to decide on which way to go, and costs are going to play a major part in such decisions. It also depends if the project is an upgrade of existing PERC lines, while the situation might be slightly different for newcomers. So it is difficult to say who will win the race, as there may not be "one runway for these two technologies". They may even coexist and compete from time to time.*

TaiyangNews: In 5 years, will we see Jolywood primarily be a backsheet company, like today, or will you primarily be a TOPCon cell/module producer – and why?

Jia Chen: *As you may already know, as of H1/2021, we are the world's largest backsheet supplier and we have been leading in TOPCon technology. Ideally, I would say we would be leading in both streams, and it is not easy to give up either of the two.*

TaiyangNews: Thank you for the interview.

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