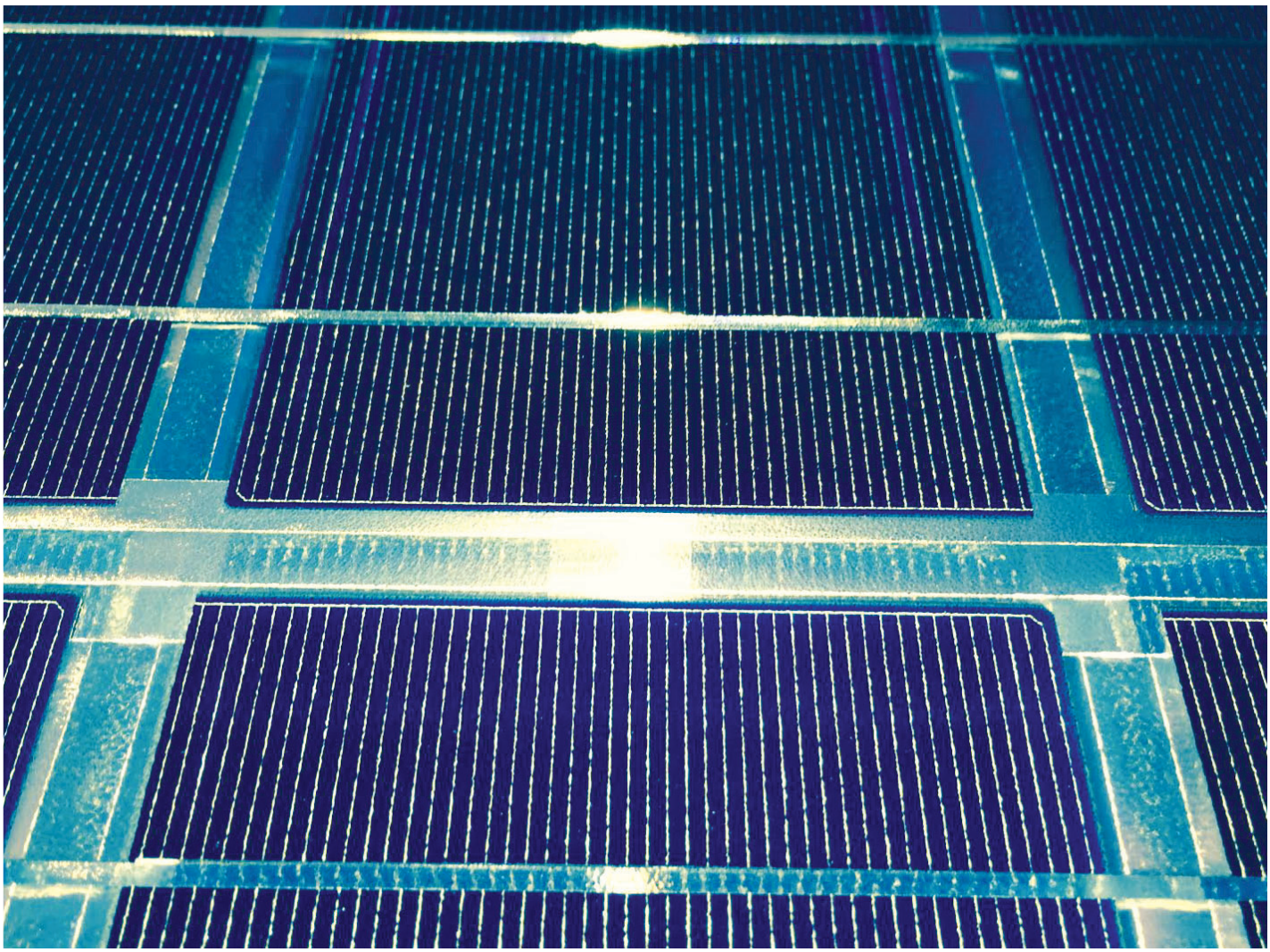
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PERC Solar Cell Technology 2016

Background, Status and Outlook

AUTHORS:
Shravan K. Chunduri, Michael Schmela



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Executive Summary

ALL solar cell manufacturers that are evaluating capacity expansion in the current investment cycle have to decide if they stick to traditional technology or opt for advanced solutions. The simplest and most attractive silicon cell technology upgrade is called **PERC**, which stands for **Passivated Emitter Rear Cell**. This report provides an overview on background, status and outlook of PERC cell technology.

PERC is an advanced silicon cell architecture that comes with a promise of higher efficiencies. At the same time, it requires only minimal changes to existing solar cell processing lines. The concept is not new, it was invented in 1983 by well known Australian scientist Martin Green.



Here comes PERC: In a showroom of JA Solar, different cell products of the Chinese vertically integrated module producer are presented to visitors - the PERC cell is placed at the top.

Opting for PERC means to add a rear passivation scheme to standard BSF cell technology. As for the implementation, it involves depositing a rear surface passivation film, which is subsequently opened to give way for formation of a rear contact. In addition, the chemical wet-bench based edge-isolation step is tweaked for rear polishing. **The key aspect of PERC technology is to deposit the rear passivation film**.

As for the rear passivation material of choice, **silicon oxynitride was used in the early days of PERC development**, and cell makers, like SolarWorld, have used it for commercial production. In the meantime, aluminum oxide has taken over as the dominating material for rear passivation. This dielectric fulfills two primary requirements - providing the field effect passivation enabled by its high fixed negative charge density as well as the ability to reduce the interface density by saturating the dangling bonds on the silicon rear surface. Like PERC technology, the passivation properties of aluminum oxide were identified long back, in 1989 - but got somehow lost until these findings were re-discovered by European researchers in 2006. But in order to fully serve its rear passivation duties, aluminum oxide needs to be combined with a capping film - silicon nitride, which protects the rear passivation film from metallization. In addition, since aluminum oxide is typically thin, the silicon nitride film compensates for the rear passivation stack thickness to safeguard internal reflection at the cell's backside.

The **deposition of aluminum oxide can be accomplished by 4 well known deposition technologies** that have been tweaked to apply this dielectric. While **sputtering** tools are currently not being offered for commercial production, there is little demand for **APCVD**. The two technologies for aluminum deposition mainly considered by commercial cell producers are **PECVD** and **ALD**. PECVD has the highest market share. It is not only very well known in PV manufacturing for depositing silicon nitride, PECVD enables deposition of aluminum oxide capped with silicon nitride in the same go. ALD results in higher quality of the deposited film than PECVD, but the processing line requires an additional PECVD tool for applying the capping layer.

Centrotherm, Manz, Meyer Burger, Semco, Singulus are offering PECVD tools for deposition of aluminum oxide, while Beneq, Levitech, Picosun, SoLayTec supply production-scale ALD systems.

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Schmid Group offers APCVD systems.

The rear passivation film composition and thickness changes according to the deposition method. Relatively thin films of about 5 to 6 nm deposited with ALD are sufficient to provide superior passivation compared to films applied with other methods. For both APCVD and PECVD, the recommended thickness of the aluminum oxide is about 15 to 25 nm, whereas the capping layer thickness range remains the same - at 100 to 120 nm.

Film thickness also plays a role in processing costs, which are highly influenced by TMA consumption. ALD scores best as thin layers can do the rear passivation job. TMA consumption is only about 2 to 3.3 mg per wafer for ALD tools, 9 to 10 mg for PECVD, while APCVD requires 15 mg per wafer to deposit a film with the required passivation quality. All these deposition tools have above 90% uptime.

After the rear passivation stack is deposited, the PERC cell architecture involves opening this stack at certain areas to give way to the aluminum and form the rear contact with the silicon. **Lasers are predominantly used for stack opening, but an option exists for using etching pastes**. Nearly every known laser solutions provider in the solar industry is offering products. The important aspects when choosing a laser system are low cost, high lifetime of components and high throughput. The use of nanosecond laser sources, for example, is employed by laser systems company InnoLas and causes a light surface damage that complements the PERC rear metallization process.

Rear polishing is a third step needed for PERC cell production over the standard process. But no additional tools are required, only a change in in wet benches that are used for junction separation. A further wet-chemical bench is only added to the line if it is designed to use lasers for edge isolation.

There are different metallization pastes on offer for PERC cells. Non-fire-through BSF and non-reactive tabbing pastes are used. Aluminum pastes have to establish a contact via the open area formed with lasers, at the same time, it should not cause any damage to the underneath passivation layer. The attributes are nearly the same for tabbing paste - not fire through the passivation layers but exhibit good

INNOLAS solutions

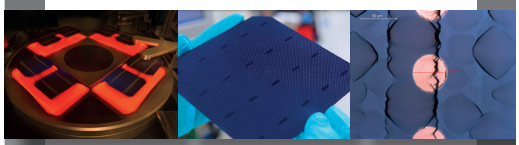
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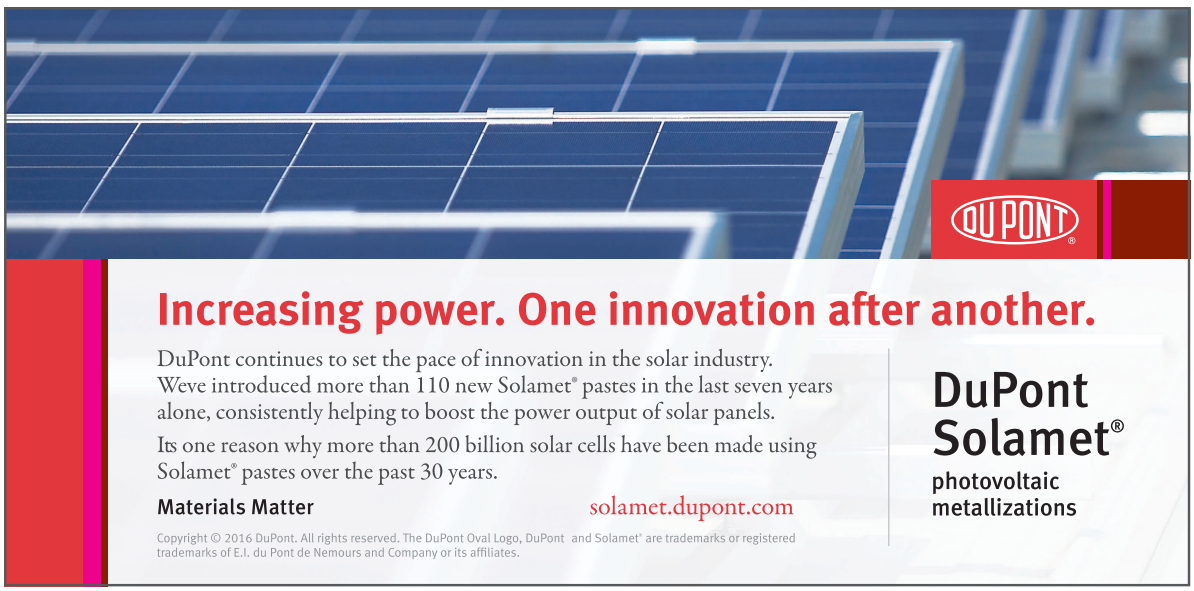
adhesion and solderability. The leading paste makers all have special PERC products on offer: While DuPont, for example, is offering a complete metallization paste pack for PERC processing; Heraeus has on offer formulations for rear busbars and front contacts, omitting local BSF paste.

While these are the bits and pieces of PERC, nearly every deposition tool supplier is offering a package line for PERC. Short **product descriptions** are given on page 29.

While the above sections deal with equipment and material of PERC cells, we have looked at the performance potential at commercial scale. As of Dec. 2015, Trina holds the world record for monocrystalline PERC at 22.13% efficiency (status: report publication date: March 15, 2016). The Chinese company is also leading in the multicrystalline segment with an efficiency level of 21.25%. The German HELENE research project, which is coordinated by SolarWorld, targets 22.5% efficient PERC mono cells by the end of 2017. **Research institute ISFH has modeled that PERC cells can attain a 24% efficiency level**.

As new record efficiencies are quickly changing for PERC, commercialization of the technology is in full swing. We estimate that **4.9 GW of PERC capacity was installed in 2015, resulting in about 3 GW of PERC cell production. In 2016, the cumulative production capacity could reach 11.8 GW, and 8.1 GW PERC products could hit the market**.

Like any other technology, PERC faces challenges. Additional investments required to add machinery or to start new lines, product bankability, data supporting the long term reliability of aluminum oxide, stable operation of production tools are teething problems. The industry is supposed to overcome these issues as it gains more experience using the technology. The major concern is the so-called **Light Induced Degradation (LID) effect**, which is especially associated with multicrystalline PERC cells today. LID can cause module power losses of up to 10%. Its root cause is not completely understood. However, the first companies - QCells and REC - say they have found the remedy and have started mass production of multicrystalline PERC cells. In consequence, wider adaption of multicrystalline PERC will take until the rest of the industry has understood this effect as well - but that is likely only a matter of time. While LID is also associated with monocrystalline PERC cells, the cause and cure are the same as for standard cells, where the issue has been solved. **Overall, PERC seems to be absolutely ready for prime time**.



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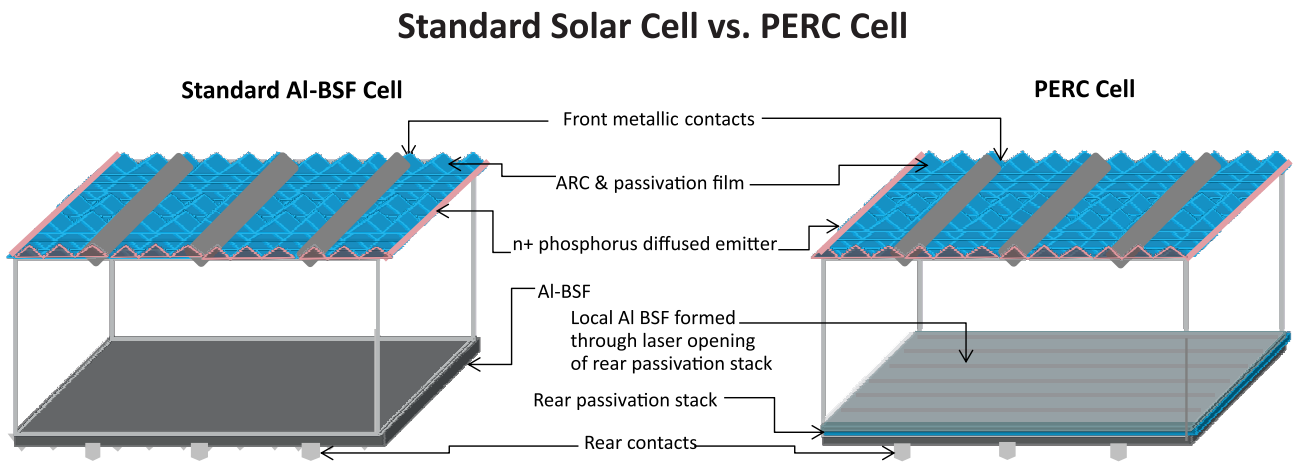
1. Introduction of PERC

SOLAR cell efficiency is not just a quality criterion, if accomplished the right way it can strongly decrease cost for the module - and in the end for generating solar power. For this reason, increasing cell efficiencies has been and will be a top priority for the PV industry.

The efficiency improvement has been taking considerable big leaps of about 0.3% per year over the last 5 years, according to ITRPV. The average cell-level efficiency in 2010 for monocrystalline cells was about 18%, which has been increased to about 19.5% in 2015, whereas multicrystalline cell performance improved by 1.5% absolute from 16.5% to 18% in the same time span. This considerable efficiency development has been attained by means of optimization as solar cell processing has hardly changed over the last decade.

But everything has a limit and so does the scope for optimization. The majority of developments that has yielded in the above mentioned performance gains were mainly focused on the sunny side of the solar cell. In order to keep pace of efficiency improvements, the PV industry has shifted its focus to the rear side. To be precise, now it is a lot about passivating the rear surface of a solar cell and accordingly modifying the metallization scheme. These rather simple changes adapted to standard solar cell processing entitle the produced silicon slices for a new name - **PERC**, which stands for **Passivated Emitter and Rear Cell**.

The PERC structure is a natural progression from the standard Back Surface Field (BSF) cell architecture. This BSF-based cell type suffers from some inherent limitations, which are becoming more apparent with the industry's focus to increase cell efficiencies. The metallic film of aluminum - which is applied on the rear side of the cell to serve as BSF - cannot support the efforts in reducing rear recombination velocities, say less than 200 cm/s. Only 60 to 70% of infrared (IR) light reaching the rear aluminum is reflected back. These electrical and optical losses can be greatly reduced by applying an additional dielectric passivation layer on the rear side - and that's PERC. This concept deals only with the optimization of the rear surface, especially aiming at reducing recombination losses on the cell's dark side, and it is fully independent from the front side. That means, any progress on the front side, such as employing innovative metallization concepts and improved junction properties, compliment the effort to improve cell performance with PERC architecture. The concept is also relatively simple to implement in production - only 2 to 3 additional steps need to be added to the standard processing sequence.



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Few changes: The PERC architecture is all about adding rear surface passivation to the standard cell, as shown in this graphic.

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The PV industry is increasingly getting excited about this rather simple means to improve efficiency - PERC is now the talk in solar town. However, PERC is not new but an over 3 decades old concept. Leading PV scientist Martin Green and his associates from the University of New South Wales in Sydney have first proposed this concept in 1983 and published a technical paper in 1989, when they announced a then world record efficiency of 22.8%. While modules made with these record cells served some niche applications, such as solar racing cars, this technology was not able to enter the mainstream. These days are over - and the commercial days of PERC have arrived. After the big crisis from 2011-2013, the first cell manufacturers started to upgrade their lines with PERC. And a big chunk of the new production capacity that had been announced in 2015 will use PERC architecture. Several cell makers have also announced new record performance levels by implementing PERC structures. When we visited the 15th PVCEC conference in Beijing in October, you could even see companies exhibiting modules with PERC cells, although their lines did not exist at the time. But a 60-cell mono module series with up to 315 W and equal to 18.9% efficiency - which Taiwanese module producer Winaico, for example, introduced at the PV EXPO in Tokyo in early March 2016 - is pretty impressive for a panel using 'slightly' modified standard cells. All in all, PERC is the next big thing in PV processing - the International Technology Roadmap for Photovoltaic (ITRPV) 2016 anticipates about 20% of solar cells produced globally in 2018 will be based on PERC-like architectures (including PERT and PERL). The previous roadmap had expected this level to be attained already in 2017 - but for PERC alone. The 2016 roadmap believes that the share of PERC-like cell structures will increase to 30% by 2020, and these cell technologies will represent close to half of all solar cells (46%) produced in 2026. In the 2015 edition, it estimated that PERC alone would increase to 35% by 2019. Time will tell.

The huge potential of this technology motivated us to prepare this in-depth report on PERC. The study focuses on processing of PERC cells, provides background on materials and production technologies. It also provides an overview on the development of efficiencies and the status of commercial implementation of the technology. Finally, the study discusses the various challenges PERC is facing - from degradation effects to competing cell technologies.

2. Processing PERC Cells

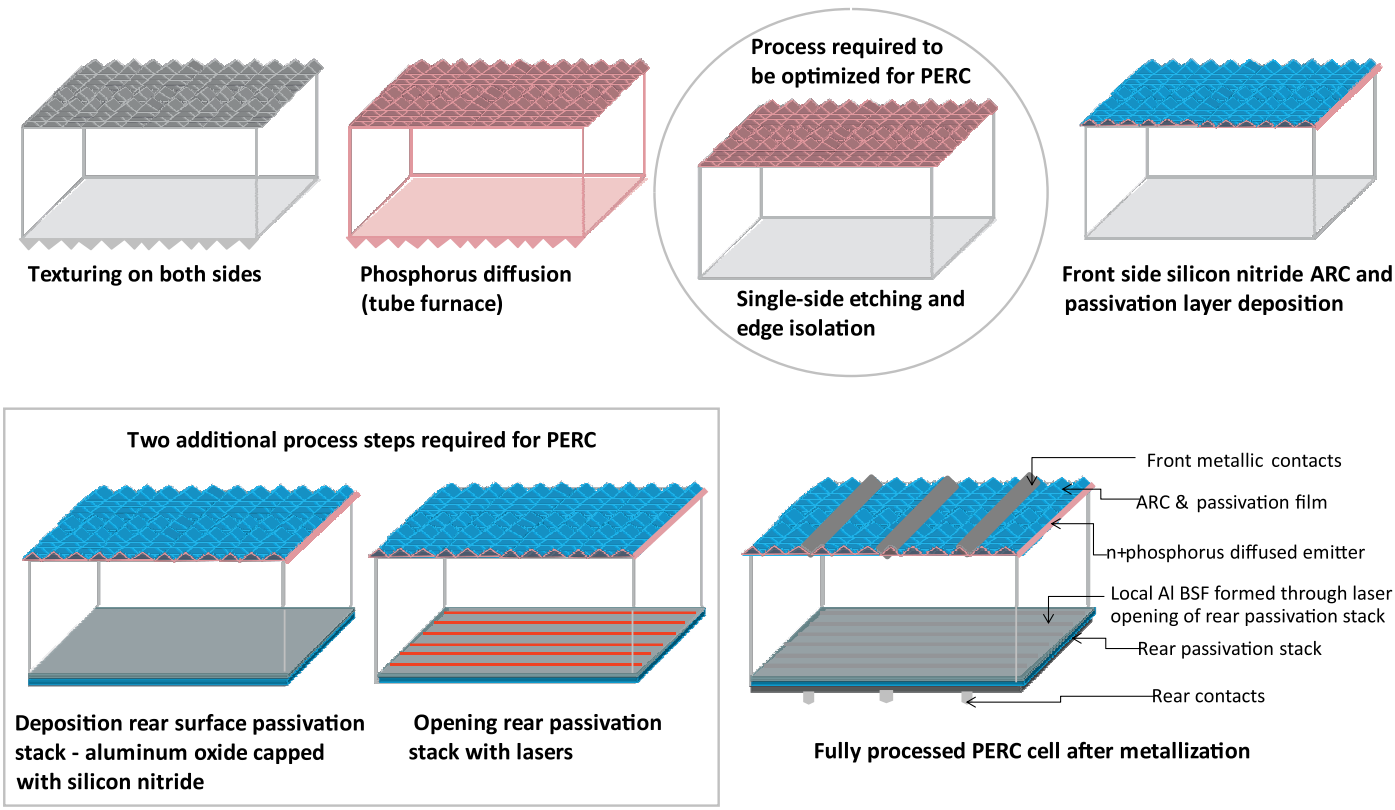
ON the processing front, PERC involves depositing a rear surface passivation film, which is subsequently opened to give way for formation of a rear contact - these are the two important additional steps over standard solar cell processing (see info-graph on page 9). In addition, the chemical wet-bench based edge-isolation step is tweaked for rear polishing. That means texturing accomplished on both sides of the wafer is removed only on the rear side by etching off the pyramid structure. The degree of polishing changes from case to case. Thus, a passivation film deposition system and a film opening system - that could be either laser based or uses a chemical path - are additional tool sets typically hooked up to standard cell processing lines. Production lines based on laser edge isolation, which is rare these days, need to add a wet-chemical bench for rear polishing.

2.1 Basics of Passivation

BEFORE going into the details of PERC technology, we provide some basics of passivation.

Nothing is perfect - even a carefully grown silicon ingot cannot escape from inheriting some crystallographic defects. On top, a very basic step of sawing wafers from the ingot itself causes 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. The impurities and defects that are present in the bulk and on the surface of the silicon wafer adversely affect the performance of a solar cell. Passivation is a process in which these defects are made inactive

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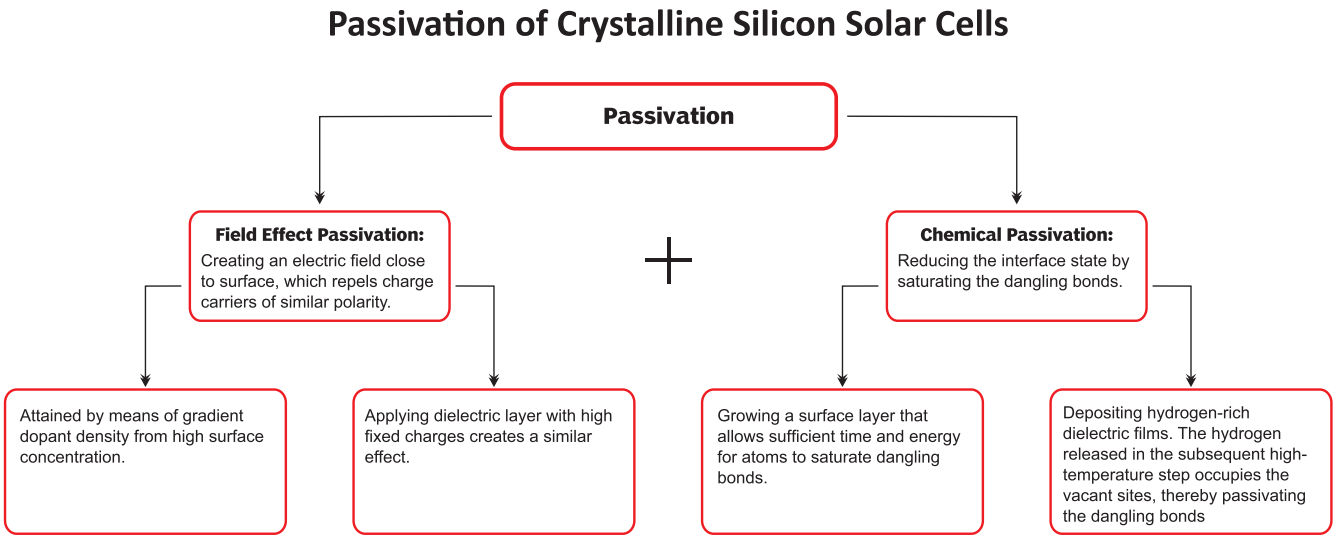
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Easy upgrade: Changing a standard silicon cell line to PERC technology requires two pieces of additional equipment - devices for rear passivation and laser structuring, as shown in this process flowchart.

to reduce the surface recombination of charge carriers, safeguarding the cell efficiency.

Passivation can be attained by two complementing methods - strongly reducing charge carriers of one polarity reaching the surface and 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. This hydrogen occupies vacant sites of dangling bonds, thereby pacifying them. This method is called **chemical passivation**. There exists another mechanism **- 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. Alternately, applying a dielectric layer with high fixed charges also creates an electric field gradient near the surface, which provides field effect passivation (An info-graph on page 10 explains the different ways of passivation for c-Si cells.).

Silicon nitride has become the most reliable passivation material for the sunny side of a standard cell. That is because of its superior antireflective properties as well as its ability to provide a good field effect passivation together with a moderate reduction of the interface states. As for the rear surface, the current state of art is to apply metallic aluminum that alloys with silicon during a firing step to form a p-type region acting as BSF. This Al-BSF is devised just to mimic the field effect passivation, which



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Passivation: Be it rear or front, silicon surface passivation can be realized by two complementing methods - field effect passivation and chemical passivation, both of which can be attained on two different ways, as shown in this flow chart.

means that when designing the standard solar cell structure, the chemical passivation aspect of the cell's dark side was completely neglected. The PERC concept is all about adding full-scale rear surface passivation attributes to standard cells.

2.2 Rear Passivation

2.2.1 Materials for Rear Passivation

WHEN looking for the suitable material for rear passivation, natural attention goes to silicon nitride - a kind of universal passivation material, at least regarding to high-volume manufacturing. Unfortunately, silicon nitride is no option. While the material can provide chemical passivation with proven track record for the sunny side of the cell, it won't work for the rear. If silicon nitride is applied on the p-type surface, it induces an inversion layer underneath the film due to its high density of fixed positive charges (up to $10^{13}/cm^3$). If this inversion layer is connected with the base contact, it causes a parasitic shunting and triggers additional losses in short circuit current densities.

2.2.1.1 Aluminum Oxide - the Ultimate Choice

A rear surface passivation material should have a high fixed negative charge, while at the same time having the ability to provide chemical passivation. **Aluminum oxide** meets these expectations. Rudolf Hezel and his team from the University of Erlangen-Nuremberg in Germany identified these excellent passivation properties of aluminum oxide back in 1989in a technical paper (*Low Temperature Surface Passivation of Silicon for Solar Cells*), which they published in the Journal of the Electrochemical Society. But this concept somehow got lost in the archives until it was rediscovered in 2006 by a research group from IMEC in Belgium (*Very Low Surface Recombination Velocities on p-type Silicon Wafers Passivated with a Dielectric with Fixed Negative Charge. Authors: G. Agostinelli et al.*) and Eindhoven University of Technology (TU/e) (*Ultralow Surface Recombination of c-Si Substrates Passivated by Plasma-Assisted Atomic Layer Deposited Al2O3. Authors: B. Hoex et al.*). From then on, aluminum oxide has become the ultimate candidate for passivating a p-type surface of a silicon cell,

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even if large-scale commercialization had to wait another decade. What really makes aluminum oxide so special is its very high density of fixed negative charges of up to $10^{13}/cm^3$. Most of the other passivation films, such as silicon oxide and silicon nitride, have positive fixed charges. With aluminum oxide, the fixed charges are located right at the interface between aluminum oxide and the interfacial silicon oxide grown on the silicon wafer during the deposition process, which ensures an effective field effect passivation. Aluminum oxide also scores high in chemical passivation. It acts as an effective hydrogen reservoir supplying hydrogen to saturate dangling bonds on the wafer surface during thermal treatment steps. As for the optical properties, these films with a band gap of 6.4 eV are transparent to the portion of sunlight that is relevant to solar cell applications. The only downside is its rather low refractive index of 1.65, which makes aluminum oxide less suitable for being a single layer antireflection film on the emitter side; however, the dielectric very well fulfills the job of back reflector.

2.2.1.2 Other Dielectrics on the Radar - Silicon Oxide

WHILE aluminum oxide is an ideal fit, several other materials were also considered to take the role of the rear passivation film. Thermally grown silicon oxide is well known to provide good surface passivation on lightly doped p-type surfaces, such as the rear side of a solar cell. It provides better interface state reduction than the other contemporary passivation schemes. Unlike any other deposition process, this one actually consumes silicon - about 45% of the layer thickness is formed by using silicon from the wafer surface. When the grown oxide layer is about 100 nm, it also functions as reflection layer at the rear side. But the thermally grown silicon oxide is not stable when covered with aluminum and exposed to temperatures above 500 ^{o}C, which actually happens in typical solar cell processing. The stability issue can be circumvented by capping it with silicon nitride, but the material has never entered the mainstream for several other reasons: First, the process of growing thermal oxide is slow and increases the thermal budget per cell. Second, the required high processing temperature of above 900 ^{o}C is a threat to the silicon bulk's lifetime, especially for multicrystalline material. However, companies like Semco Engineering from France are offering refurbished diffusion furnaces operated at a slight vacuum to grow uniform thermal oxide.

On the other hand, time tested PECVD is a very PV friendly way of applying silicon oxide at low temperature. It is a simple means, too. Compared to silicon nitride deposition, the process involves changing one precursor gas - supplying nitrous oxide instead of ammonia -, while silane is still in use. The resulting deposited layer contains some hydrogen and also some nitrogen, the latter due to employing nitrous oxide as a source for oxygen. Thus, the deposited layer is rather a **silicon oxynitride** film with a much lower amount of nitrogen. This material does provide chemical passivation, but it fails in terms of the field effect passivation due to the presence of net positive charges. Establishing a reliable contact on the surface deposited with a silicon oxynitride film that exhibits good passivation properties is not that easy. That's probably the reason why Centrotherm from Germany is the only company that has been promoting production tools to support the silicon oxynitride based rear passivation solution, and SolarWorld was its largest client in the "early" commercialization days of PERC. But in 2015, the German equipment maker has also started offering rear passivation tools based on aluminum oxide, while SolarWorld began to expand into this dielectric as well - in early 2015, it signed a technology partnership with Meyer Burger to upgrade 400 MW of its cell lines.

PECVD deposited **silicon carbide** using methane as the source of carbon has also been evaluated for rear surface passivation, but like silicon oxynitride it also has the same fixed positive charge, which makes the dielectric less suitable for that purpose. Intrinsic amorphous silicon semiconductor films, also deposited with PECVD, have outstanding passivation properties. But the well known limitation of these layers - unstable above 450 ^{o}C - makes them not compatible for PERC type cell architectures (see table on page 12).

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Characteristics of Different Dielectrics

Dielectric	Suitable Wafer Type	Commercially Feasible Deposition Process	Film Stability in Post Deposition Processes	Field Effect Passivation	Chemical Passivation	Overall Passivation Quality	Processing Cost	Commercial Status for PERC	Limitations
Aluminum Oxide	Mono / Multi	PECVD, ALD, APCVD, Sputtering	✓✓	✓✓✓	✓✓	✓✓✓	✓✓	✓✓✓	Employs expensive precursor TMA and is a relatively new material
Silicon Oxide (Thermally grown)	Mono	Thermally grown at high temperature	✓*	✖	✓✓✓	✓✓✓	✓	✓	Commercially viable solution for depositing very thin layers, which is not a self sufficient passivation film. Thus, it requires a capping with a stack of aluminum oxide and silicon nitride
Silicon Oxynitride	Mono	PECVD	✓✓✓	✖	✓✓	✓✓	✓✓✓	✓✓	Metallization process needs very careful optimization; mainly promoted for mono
Silicon Carbide	Mono / Multi	PECVD	✓✓	✖	✓✓	✖	✓✓✓	✖	High fixed positive charge creates inversion layer
Amorphous Silicon	Mono / Multi	PECVD	✓**	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓	Not suitable for standard processing conditions, but low temperature processes can yield outstanding results (e.g. hetero-junction cells)
Silicon Nitride	Mono / Multi	PECVD	✓✓✓	✖	✓✓	✖	✓✓✓	✖	High fixed positive charge creates inversion layer

Legend: ✓✓✓ Very Good; ✓✓ Good; ✓ Acceptable; ✖ Unacceptable

Notes: *unstable >500°C when covered with aluminum thus needs a capping layer; **unstable >450°C

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Best in class: Aluminum oxide is the most suitable film for rear passivation of silicon solar cells.

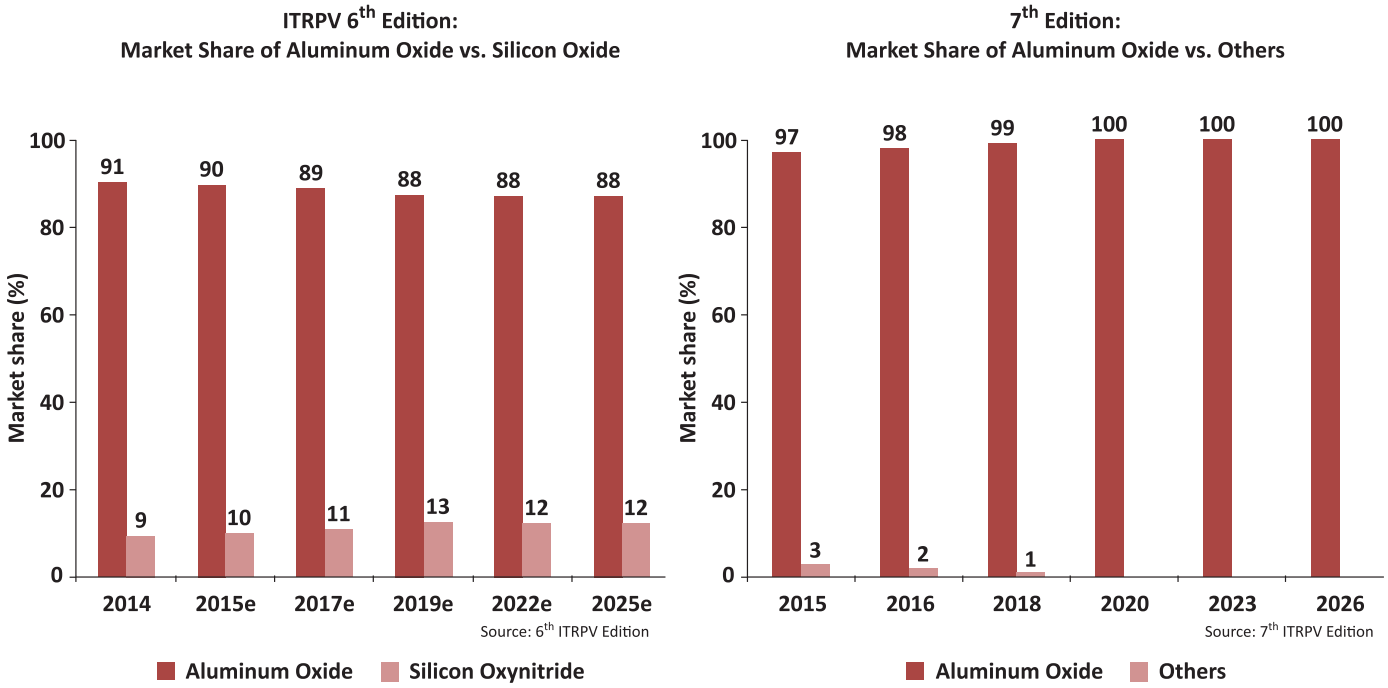
Overall, as for the choice of material for rear surface passivation of silicon cells, there are very few supporters of silicon oxide (be it deposited or thermally grown), while aluminum oxide is enjoying a near monopoly status. ITRPV has dramatically improved its forecast for this technology and estimates now that aluminum oxide will retain its lion's share of 97%, which it expects to increase to 100% by 2020; silicon oxide is not even mentioned anymore in this survey (see graph on page 13). So a more important question is how to deposit the aluminum oxide film in a cell factory - and in fact, the choice of products is big.

2.2.2 Technologies for Depositing the Dielectric Commercially

FOLLOWING the path of history is one way. Most of the PV manufacturing processes have their roots

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ITRPV's Changing Views on Shares of Rear Passivation Materials



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A true monopoly status: The 2016 ITRPV roadmap anticipates aluminum oxide to enjoy a true monopoly status by 2020, even growing its acceptance from the current level of 97% to 100% within 4 years. The 2015 roadmap had expected silicon oxynitride would account for 10% at the time – and remain in the game for the next decade. Now silicon oxynitride is not even mentioned by name anymore.

in semiconductor processing and were simply tweaked to make them suitable for PV production. This is also true for aluminum oxide. The semiconductor industry employs a method called **Atomic Layer Deposition (ALD)**, and the technology had been fine-tuned by several equipment makers to make it suitable for solar cell processing. However, nearly every deposition technology known for the application of silicon nitride has been optimized for the deposition of aluminum oxide. **Sputtering** belongs to this category, as well as the **PECVD** platform. Even APCVD is now on the list. **APCVD** was once used in PV cell making to deposit titanium oxide as an anti-reflective coating, but was completely replaced by superior silicon nitride applied with PECVD.

Capping with Silicon Nitride

Whatever the material and the means of deposition, the dielectric layers cannot fulfill the requirements of rear passivation all alone. It primarily needs a protective capping film to save it from the aluminum BSF paste. Otherwise, during the firing step, screen-printed metallic aluminum would penetrate though the film, damaging it completely. The rear passivation layer is also expected to take care of the internal reflection at the back of the solar cell. This brings in a new metric of a minimum film thickness requirement, which is at 100 to 120 nm (compared to about 60 to 70 nm on the front). Depositing such a thick rear passivation film, especially in case of the aluminum oxide film, would not make economic sense due to the high cost of its precursor. Adding to that, depositing thicker aluminum oxide adversely affects the tool's throughput. The other quality properties of the film, such as mechanical strength and resistance to blistering, are better when the film is rather thin. That means the aluminum oxide film has to be thin, and at the same time it has to be thick enough to safeguard

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optical properties. Thus, applying a thin layer of aluminum oxide and cap it with silicon nitride is the most amicable solution - and the method used to deposit this capping layer is the very obvious PECVD, as employed for the sunny side. But this boundary condition not only applies for aluminum oxide, it is equally valid for rear surface passivation configurations relying on silicon oxynitride.

2.2.2.1 ALD

WHILE using PECVD for depositing silicon nitride is a well-known and mature process, the crux of the PERC process lies in depositing the primary rear passivation film - aluminum oxide. As for its deposition methods, the choice is wide. Atomic Layer Deposition was employed by research groups from IMEC and TU/e, when aluminum oxide was re-introduced to the PV industry (see box for details on ALD).

In ALD, the aluminum oxide is grown layer by layer and the deposition process is governed by two self-limiting half-reactions:

$Al(CH_3)_3 + Si\text{-}O\text{-}H\ (s) \rightarrow Si\text{-}O\text{-}Al(CH_3)_2 + CH_4$

$2H_2O + :Si\text{-}O\text{-}Al(CH_3)_2 \rightarrow Si\text{-}O\text{-}Al(OH)_2 + 2CH_4$

Each of these half reactions are followed by purging steps. In the first half, water vapor is adsorbed on most surfaces, forming a hydroxyl group (Si-O-H complex) on the silicon wafer surface. When trimethylaluminum (TMA) is pulsed into the reaction chamber, it reacts with adsorbed hydroxyl groups producing methane. At the end of this first half-reaction, aluminum atoms and methyl groups cover the surface. The remaining TMA molecules in the deposition chamber are no longer able to react with the surface, thereby limiting the reaction to one layer. The excess TMA along with reaction byproducts are purged away.

In order to accomplish the second half of the reaction, ALD offers two possibilities - thermal or plasma assisted. In the thermal approach, water vapor is injected into the reaction chamber, which reacts with dangling methyl groups and forms aluminum-oxygen bridges and hydroxyl surface groups. Methane is again a reaction byproduct that is pumped away along with the excess water vapor. Alternatively, this oxidation step can also be carried out by making use of plasma energy. Here, oxygen plasma is ignited above the substrate to generate oxygen radicals, which effectively reacts with methyl groups and aluminum at the surface, resulting in deposition of the aluminum oxide layer.

The beauty of ALD is that aluminum oxide layers are grown layer by layer on the atomic level, resulting in a good step coverage. There is another plus - the deposition rate is independent of the precursor supply and the process is accomplished at rather low temperatures at 100 to 350 ^{o}C. On the negative side, ALD suffers from a low deposition rate - each process cycle results in a single atomic layer growth with a film thickness ranging between 0.9 and 1.5 Å. This thickness is influenced by several parameters such as reactor design, temperature and oxidation process. But to attain the desired thickness, several of these cycles have to be repeated.

Batch-type ALD:
The ALD reactors used for semiconductor applications are batch-type reactors, in which the alternate dosing of precursor and oxidant are accomplished in the same reactor chamber. These reactors are very slow. While the actual processing time is in the milliseconds scale, the ancillary processes such as purging along with pumping down the chamber at the end of each step accounts for few seconds. As

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a result, traditional ALD systems typically have a low throughput of about 50 wafers per hour, which is a no go for PV manufacturing.

To overcome this limitation, equipment makers have developed innovative product platforms. The operating principle has been kept exactly the same - alternate dosing of the precursor and oxidant, and purging accomplished in the same reactor chamber -, but the products have been adapted to a larger batch size. ALD inherently supports such modifications as increasing the batch size or processing substrates with a larger surface area has a limited effect on the cycle time. Companies like **BeneQ** and **Picosun** from Finland - which have a background of serving the semiconductor industry with their ALD products - are pursuing this approach. In addition to increasing the batch size, accomplishing the preheating externally as well as opting for automatic wafer handling helps in increasing the throughput of the batch reactors. However, these time-based ALD systems suffer from an inherent limitation that aluminum oxide is deposited on wafer rims and peripherals of the front side, known as wraparound deposition. Beneq has been working on this limitations, but the current status is not known as Beneq declined to provide any details, while Picosun has not replied to our inquiry. Japan's Ulvac has also developed a R&D scale ALD system in 2014, but the later developments are not known as the company has not answered our inquiry.

Inline-type ALD:
Next to batch and time-based ALD, you can move the technology into a spatial domain. This means that instead of alternate pumping of the reactants into one chamber, the reactor is divided into separate zones, in which the wafer is exposed to the precursor. These reactor zones are separated with inner gas curtains. When operated properly, the gas shields can act as gas bearings, enabling the wafer movement in a frictionless manner. The gas bearings also act as diffusion barriers between the reaction zones, preventing cross reactions and parasitic deposition on the reactor walls. Most importantly, speeding up the rate of accomplishing the two half-reactions in combination with redundancy of the purge steps allows for very high deposition rates, while maintaining the typical ALD attributes like film quality and conformality.

Dutch companies **Levitech** and **SoLayTec** have designed their products based on this spatial ALD principle. The method not only allows an inline operation mode, it is also being accomplished at atmospheric pressure, which saves a lot of time for pumping down and venting the reactor. Spatial ALD is an exclusive development for the PV industry. One more inherent advantage of spatial tools is that the deposition takes place only on a single side.

In SoLayTec's machines, wafers are moved back and forth under an injector head, typically twice per second, resulting in 4 passages per second. This leads to the deposition of 4 layers per second for a single slot injector head or 8 layers per second for a twin slot injector head. Before the wafers are subjected to the deposition in this core reactor, the wafers are preheated to 200 ^{O}C in 6 seconds. When the desired thickness of the aluminum oxide is reached by cycling the wafer through this segment of the reactor, the wafer is ejected from the core reactor. Then the substrate is cooled down for 30 seconds on a cooling track. In parallel, the next wafer in queue already enters the core reactor. This method reduces the length of the deposition chamber. But to attain a reasonable throughput, several of such chambers have to be linked in parallel. So the total throughput is more or less determined by the number of process chambers integrated into the company's system called InPassion ALD. SoLayTec's main product is a 6-module system, which has a rated throughput of 3,600 wafers per hour. The company says there is request for high throughput machines, such as a 8-module configuration with a capacity of 4,800 wafers per hour. But it also offers a smaller system with 4 modules that supports an hourly throughput of 2,500 wafers. SoLayTec is currently focusing on increasing uptime from currently around 93 to 94%, up to a level of 97%.

The difference with Levitech's philosophy is that it transports the wafers unidirectional from one end of

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the chamber to the other. With this approach, the reaction chamber looks like a long tunnel. The precursors are injected into the processing environment by means of a series of narrow channels from the top as well as the bottom of the chamber towards the wafer. The narrow gap also ensures a stable transport. The reactor is designed that TMA and water vapor do not mix on their way to the exhaust so that the undesired deposition of aluminum oxide on the track walls is avoided. Levitech calls its product Levetrack. While Levitech is aiming to attain an hourly throughput of 3,600, it is guaranteeing a production capacity of 3,000 wafers per hour with the current system. Levitech claims it has upgraded the system especially in terms of uptime and maintenance, but would not provide any details.

Overview ALD Systems for Aluminum Oxide Deposition

Company	ALD-type	Principle	Process Details	Wafer Orientation	Inline	Vacuum free Depostion	Free from Wrap Around Depostion	Incl. Deposition of SiNx on Front side	Incl. Deposition of Capping Layer	Max. Throughput (Wafers/hr)	Uptime
BeneQ* **	Time-based	Thermal ALD	Alternate dosing of precursors into the same reaction chamber; preheating is done externally	Horizontal	✖	✖	✖	✖	✖	1,600	N/A
Levitech	Spatial	Thermal ALD	Long process chamber; wafers moved in one direction	Horizontal	✔	✔	✔	✖	✖	3,000*	N/A
Picosun* **	Time-based	Thermal & Plasma ALD	Alternate dosing of precursors into the same reaction chamber; realizes thermal and plamsa ALD in same reactor chamber	Horizontal	✖	✖	✖	✖	✖	1,200	N/A
SoLayTec	Spatial	Thermal ALD	Moves wafers back and forth; multiple reactors are connected in parallel to reach desired throughout	Horizontal	✔	✔	✔	✖	✖	3,600**	94%

Legend: ✔ Yes; ✖ No

Notes: *Levitech aims to increase throughput to 3,600 W/h; **based on 6-module device - the most common configuration, an 8-module system processes up to 4800 w/h; *** BeneQ, Picosun have not replied our inquiries - throughput numbers are estimates; N/A not available

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Still quite different: ALD technology is the base, but the tool suppliers have designed very different platforms for deposition of aluminum oxide.

2.2.2.2 PECVD

SUPPLIERS of PECVD solutions for silicon nitride deposition on the sunny side of the cell have also seen the potential of PERC cell technology and accordingly worked on their products to deposit aluminum oxide. Introducing the precursor - which is again TMA - and adaption of the cleaning mechanism are more or less the two important fundamental changes that PECVD systems are required to undergo to be able to apply aluminum oxide films on the rear side of the cell. Not only the generic deposition principle of PECVD stays the same, which is the radio frequency (RF) power used to dissociate precursors at low pressure leads to depositing the required film on the substrate present in the

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chamber. Even the equipment makers' proprietary plasma generating mechanisms do not need to be changed. With so little effort required for silicon nitride deposition equipment suppliers to adapt their PECVD platforms for aluminum oxide deposition, several of such products are now on offer in the field of PERC cell production (see table, page 18).

As with silicon nitride deposition systems, PECVD tools for aluminum oxide deposition also segment into two major categories - direct plasma and remote plasma. For the latter type, which includes products offered by Meyer Burger, plasma is generated remotely and the carrier containing the substrates to be coated is passed through the plasma environment. In case of direct plasma systems, the carrier is part of the plasma generating electrode. Direct plasma deposition systems are offered from Semco, Singulus and Centrotherm. Then, Manz has developed a hybrid platform by combining the advantages of direct and remote plasma principles. The PECVD tools from these four companies are promoted for aluminum oxide. However, Centrotherm initially developed deposition systems for silicon oxynitride; only very recently it has joined the aluminum oxide club. In the following paragraphs we have provided some details for these PECVD products.

PECVD equipment market leader **Roth & Rau** (recently renamed to **Meyer Burger Germany AG**) offers a product called Multiple process Application inline Apparatus (MAiA) platform. This product range of the German company supports deposition of the silicon nitride capping layer on top of aluminum oxide in one system without breaking the vacuum. The platform further offers the possibility to coat silicon nitride on emitter side in the same stretch. That means all front and rear passivation is accomplished in one go. Meyer Burger has designed its products based on a modular platform, which enables to add a number of process modules depending on the throughput requirement. For example, the MAiA 3400, the most common configuration of the company, comes with 4 process modules for aluminum oxide deposition and 6 for silicon nitride capping, both of which are connected by means of a transport system. The setup has load locks at the point of loading and unloading end of the long reactor. The system employs 2 and 6 plasma sources, respectively. The wafers to be processed are placed on a tray with 24 slots and are coated from top. With a cycle time of 27 seconds per carrier, the MAiA 3400 has a production capacity of 3,200 wafers per hour.

Semco's rear passivation solution follows a similar method. Its PECVD reactor can also accomplish the deposition aluminum oxide capped with silicon nitride simultaneously in the same system, but it needs a separate tool for emitter passivation. Additionally, Semco recommends to add one more device for growing the thermal silicon oxide layer, prior to depositing the dielectric films. This oxide growing system is based on Semco's LYDOP diffusion furnaces platform, which operates at low pressure. It enables growing a thin and uniform layer of silicon oxide with a thickness of less than 5 nm. This film, when grown before the deposition of the typical rear passivation stack, prevents interfacial defects and Light Induced Degradation (LID), and it acts also as a good barrier for Potential Induced Degradation (PID), Semco claims. This oxide growing system, which is priced slightly lower than a diffusion furnace of the company, has a throughput of 4,400 wafers for a layer thickness ranging from 2 to 8 nm. To equate to this capacity, 2 PECVD systems for depositing the stack of aluminum oxide and silicon nitride - each tool with a rated capacity of 2,200 wafers per hour - are installed in a production line.

While rear surface passivation schemes are fundamentally based on aluminum oxide, silicon oxynitride has also been used industrially for the same purpose. **Centrotherm** has been the only advocate of this solution. The German company initially promoted its nitrous oxide upgrade for the front side of the cell as a means to prevent PID, but made it later a part of its products for its Centaurus PERC cell technology. This dielectric film is also capped with silicon nitride simultaneously in the same tool. Centrotherm converted many of its installed PECVD systems to the silicon oxynitride process during the last big PV downturn. While the process was mainly promoted for monocrystalline wafers, the company says its installed base of oxynitride equipment is about 2 GW.

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Overview PECVD Systems for Aluminum Oxide Deposition

Company	PECVD type	Principle	Process Details	Wafer Orientation	Inline	Vacuum free Depostion	Free from Wrap Around Depostion	Incl. Deposition of Capping Layer	Incl. Deposition of SiNx on Front Side	Max. Throughput (Wafers/hr)	Uptime
Centrotherm	Direct Plasma	LF- Plasma	Carrier with wafers is part of plasma generating electrode	Vertical	✖	✖	✔	✔	✖	1,600	97%
Manz	Hybrid	High power plasma (HPP)	High power plasma is employed to deposit wafers in specially desinged carrier that keeps the wafers in upright position avoiding pin marks	Vertical	✔	✖	✔	✔	✖	1,100	95%
Meyer Burger*	Remote Plasma	Linear MW Plasma	Carrier with wafers passes through remotely generated plasma	Horizontal	✔	✖	✔	✔	✔	3,200	93%
Semco	Direct Plasma	LF- Plasma	Based on vertical reactor design and carrier is still connected to electrode	Horizontal	✖	✖	✔	✔	✖	2,100	97%

Legend: ✔ Yes; ✖ No

Notes: *Formerly Roth & Rau; **As Singulus did not want to provide details for their system, the company is not listed

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Two in one: All PECVD tools come with the great advantage of depositing both aluminum oxide and silicon nitride capping in one go.

Centrotherm recently announced that it is also introducing an aluminum oxide based rear passivation solution; the first systems are in pilot production. The new product deposits the aluminum oxide and capping silicon nitride films in one go. Centrotherm says the capping layers deposited in tube furnaces have higher densities compared to layers from inline furnaces, which would ultimately result in better passivation properties. As with the silicon oxynitride products, Centrotherm is offering the upgrade packages for its installed PECVD systems to deposit aluminum oxide. The upgrade kit consists of a space-saving hardware including TMA cabinet and corresponding gas lines to supply the precursors. Centrotherm's furnace has a rated output of 1,600 wafers per hour and a cluster of two systems and shared automation, which leads to an hourly capacity of 3,200 wafers.

Needless to say, all this effort is to meet the level of Meyer Burger's MAiA tools, which have created a benchmark in the rear passivation segment. Tube furnaces are generally considered to result in better film quality, though this is difficult to quantify. But the clear advantage is their higher uptime. While Meyer Burger tools have an uptime of 93%, Centrotherm's furnaces comes with an assured level of 97%. That's only due to the difference in the machine concept. Tube furnaces also offer redundancy and have a smaller footprint. According to Centrotherm's SVP Technology & Sales, Josef Haase, his company's PECVD tool occupies factory floor space that is slightly higher than half of the inline tool's footprint. The inline furnace, on the other hand, works out to be economical in capacity expansions.

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For example, to double the throughput of an inline system, the additional capex would be around 1.5 times, while tube systems require a proportionate investment, in this case twice the amount. When it comes to system costs, Haase says, his company's systems require about 10 to 15% lower capex. Probably, such a price advantage is necessary for Centrotherm's tools to compensate its later entry.

Singulus from Germany is also a PECVD supplier offering systems for aluminum oxide deposition. But the equipment maker declined to provide any details for its products.

Manz, which made a rather late debut into the rear passivation segment, has developed a hybrid system platform that combines direct and remote plasma technology. The German company has declined to provide details for its tool, so it is not clear what exactly has changed over its first model, which was launched under the name VCS 1200 in 2013. According to a joint research paper from Fraunhofer Institute for Solar Energy Systems (ISE) and Manz, presented at the 28th European PV Solar Energy Conference (EU PVSEC) in 2013, the core concept of this PECVD tool is based on a high-power plasma source (HPP). It is a compact process station capable of processing 8 wafers at once and accomplishes coating in a static deposition process. Plasma discharge is driven by 13.56 MHz RF power with up to 12 kW. Gas inlets and exhausts are integrated into the process compartment wall. During the process, the wafers are kept vertical, which helps to keep the coating free from particles, flakes and pin marks. Manz is also offering a combined aluminum oxide/silicon nitride stack deposition system with a throughput of 1,100 wafers per hour.

2.2.2.3 APCVD

APCVD is also repositioned for the deposition of aluminum oxide. In an APCVD system, the precursors are delivered onto the hot wafer surface in the process chamber. This thermal energy dissociates the reactants and results in the deposition of a desired dielectric. Unlike PECVD, this process is accomplished at atmospheric pressure, eliminating costs and complexity associated with creating a low-pressure process environment. The deposition rate and film quality are the function of the precursor ratio and their supply rate, process temperature and speed of substrate transport system. APCVD also employs TMA as a precursor, but according to a paper (*Surface Passivation of Crystalline Silicon by APCVD Aluminum Oxide*) from Australian National University (ANU) presented at the 26th EU PVSEC in 2011, other low cost materials such as Triethyldialuminium tri-(sec-butoxide) (TEDA-TSB) can also be used.

The APCVD process has a number of undeniable advantages - it is accomplished at atmospheric pressure (no vacuum pumps and no special hardware is required to maintain low pressure deposition conditions) and on top, very high deposition rates can be attained. But aluminum oxide layers deposited with APCVD require PECVD to deposit the capping layer - like ALD. On the other hand, the deposited films have a thickness uniformity deviation of +/- 5%, which is close to PECVD films, although this deviation is high compared to a value of +/- 3% that is typically specified for layers applied with ALD.

Currently, only **Schmid Group** is promoting an APCVD product. In its tools, the wafers are preheated in a specific section of the reactor before they are delivered to the deposition chamber. A muffle structure is included within the heating section of the system to realize a controlled process environment containing the precursor chemicals, which are delivered precisely by the injector assembly. The same system is also responsible for evacuating the unused gases and process byproducts. A conveyor moves the substrates to be deposited through this processing environment. A water-cooled hearth is provided to cool the belt and substrates after deposition. These systems are integrated with specially designed injector heads, which are capable of delivering at least three types of gases in parallel jet streams, homogeneously distributed over the wafer surface, while still keeping

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Overview APCVD Systems for Aluminum Oxide Deposition

Company	Deposition Principle	Principle	Process Details	Wafer Orientation	Inline	Vacuum free Depostion	Free from Wrap Around Depostion	Incl. Deposition of SiNx on Front Side	Incl. Deposition of Capping Layer	Max. Throughput (Wafers/hr)	Uptime
Schmid	APCVD	CVD accomplished at atmosphereic pressure	Specially-designed injector heads deliver precursors in parallel streams onto hot wafer homogeneously for deposition	Horizontal	✓	✓	✓	✗	✗	4,000	93%

Legend: ✓ Yes; ✗ No

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Half the job: On the plus side, APCVD tools support high deposition rates, but require additional PECVD systems to deposit the capping silicon nitride layer.

them separated until they come in contact with the hot substrate. Schmid offers two models - one employs ceramic rollers for transporting the wafers, an older version uses a metallic conveyor. While the latter supports a throughput of 1,500 wafers per hour, the newer reactor comes with a production capacity of 4,000 wafers per hour.

2.2.2.4 Sputtering

SPUTTERING is the only deposition technology that deposits aluminum oxide without using any chemical gases. It simply employs aluminum targets that are reactively sputtered in an oxygen/argon atmosphere. Thus it also does not require abatement systems. The important process parameters for sputtering are oxygen supply, wafer temperature, process pressure and power. Oerlikon offered a production scale sputtering system called Solaris. But end of 2014, the Swiss equipment maker sold its

Overview Sputtering Systems for Aluminum Oxide Deposition

Company	Sputtering Type	Principle	Process Details	Wafer Orientation	Inline	Vacuum free Depostion	Free from Wrap Around Depostion	Incl. Deposition of Capping Layer	Incl. Deposition of SiNx on Front side	Max. Throughput (Wafers/hr)	Uptime
*	Reactive Sputtering	Target is sputtered in presence of gas(es)	Aluminum target is sputtered using reactive oxygen in argon atmosphere	Horizontal	✓	✗	✓	✓	✗	1,150	93%

Legend: ✓ Yes; ✗ No

Notes: * Data based on sputtering system, Oerlikon offered in the past

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Aluminum targets: Sputtering is the only technology that does not employ any chemicals for deposition of aluminum oxide, but it has not yet entered mainstream production for this application.

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Advanced Technologies Segment with the sputtering system to Evatec AG. The new technology owner is not promoting the tool for rear surface passivation application but mainly for rear side metallization. Screen Finetech Solutions from Japan announced late last year that it is also developing a sputtering platform for the deposition of aluminum oxide. However, sputtering has not yet entered the main stream for rear passivation applications.

2.2.3 Thickness of the Final Rear Passivation Film

AFTER knowing what and how to deposit, the next logical question would be to quantify it - how much to put down? There is no straightforward answer. And there is also no standard for the optimal thickness for each layer in this passivation film configuration. But a common approach is to keep the aluminum oxide rather thin, while silicon nitride fills the gap to qualify for the minimum thickness requirement of about 100 to 120 µm for the rear passivation stack to safeguard the rear internal reflection. The required thickness of aluminum oxide indeed changes according to the method of deposition.

Relatively thinner films deposited with **ALD** are sufficient to provide superior passivation compared to films applied with other methods. In fact, ALD tool suppliers have been very successful in reducing film thickness. During the early days of aluminum oxide development, around 2008-09, a film thickness of 30 nm was common. Now both SoLayTec and Levitech are characterizing a film thickness of 5 to 6 nm as more than sufficient. The capping silicon nitride layer is typically about 100 nm. But there is no upper limit on the silicon nitride capping layer. There are companies that use up to 200 nm thick silicon nitride in pursuit of gaining higher efficiency. According to Levitech's CTO Koen Vanormelingen, his company in association with ECN worked on a bifacial PERC concept, in which 5 to 6 nm of aluminum oxide is used without any capping. For the emitter on n-type cells the film could be even thinner - according to Levitech as thin as 2 nm. ALD provides a very good step coverage, which enables the use of very thin films.

When **PECVD** is the choice of deposition technology, relatively thicker films are required to attain the desired passivation properties. Films of 20 to 25 nm are common with PECVD. There is no big difference regarding silicon nitride capping films- about 100 to 120 nm thick films are employed. Centrotherm recommends a wide range of 15 to 25 nm of aluminum oxide capped with 100 to 120 nm of silicon nitride. The spec given by Meyer Burger is the same for the capping film, but slightly deviates for aluminum oxide at 20 to 25 nm. Schmid is also recommending the same configuration for films applied with its **APCVD** tools (see graph on page 22).

2.2.4 Comparing Materials & Deposition Technologies

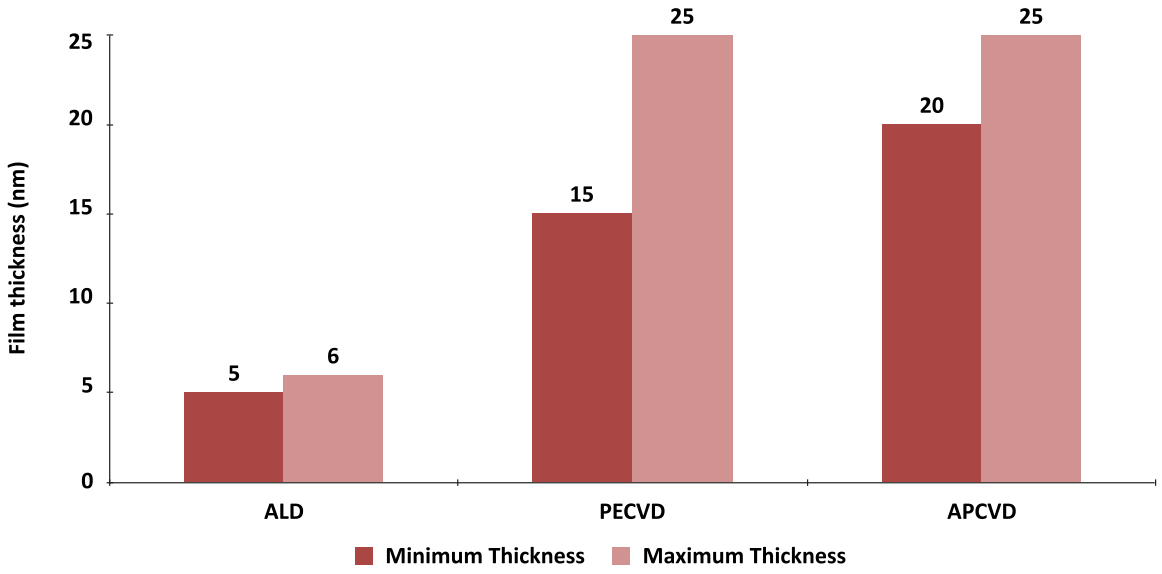
OVERALL, a large variety of solutions are available for rear passivation. Every approach comes with a set of benefits and certain limitations.

2.2.4.1 Silicon Oxynitride

AS for the passivation material, thermally grown silicon oxide, as promoted by Semco, is only playing a supporting role and is not a mainstream solution. Silicon oxynitride deposited with PECVD was the first to enter the commercial space and it has been the most cost effective rear passivation material by far. Gunter Erfurt, former CEO of SolarWorld Innovations GmbH and the new CEO of Meyer Burger(Germany) AG (formerly Roth & Rau), as well Radovan Kopecek, Managing Director of the International Solar Energy Research Center (ISC) Konstanz, consider silicon oxynitride a top passivation material. The process uses a low cost precursor - nitrous oxide. It is also simple to implement in production even with the existing PECVD tools. The precursors are gaseous as with silicon nitride. According to Centrotherm's Haase, silicon oxynitride is the only proven technology with more than 5 years production experience, apart from the standard. However, it earned only few followers. The

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Required Thickness Of Aluminum Oxide For Different Deposition Technologies



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Method matters: The required thickness of the aluminum oxide film to attain sufficient passivation differs with deposition technology - while thinner films deposited with ALD can do the job, relatively thicker films are required when using PECVD or APCVD.

passivation configuration based on silicon oxynitride is still a compromise, as the material only provides chemical passivation, but misses the field effect part due to its fixed negative charge. This dielectric has mainly been beneficial for monocrystalline wafers, while the results were not up to the mark for multicrystalline material. Moreover, it has been challenging to establish reliable contacts on the rear side passivated with silicon oxynitride in mass production.

2.2.4.2 Aluminum Oxide

THE above mentioned limitations of silicon oxynitride likely have pushed even the early adopters of the technology to search for an alternate passivation material. In March 2015, the German integrated wafer-to-module maker SolarWorld ordered PECVD tools from Meyer Burger for deposition of aluminum oxide to upgrade 400 MW of its cell lines at its facility in Freiberg, Germany. This is a clear indication that SolarWorld, which was the first to commercialize silicon oxynitride based rear passivation cell architecture, has also started using aluminum oxide. Aluminum oxide is currently enjoying nearly a monopoly status in this segment.

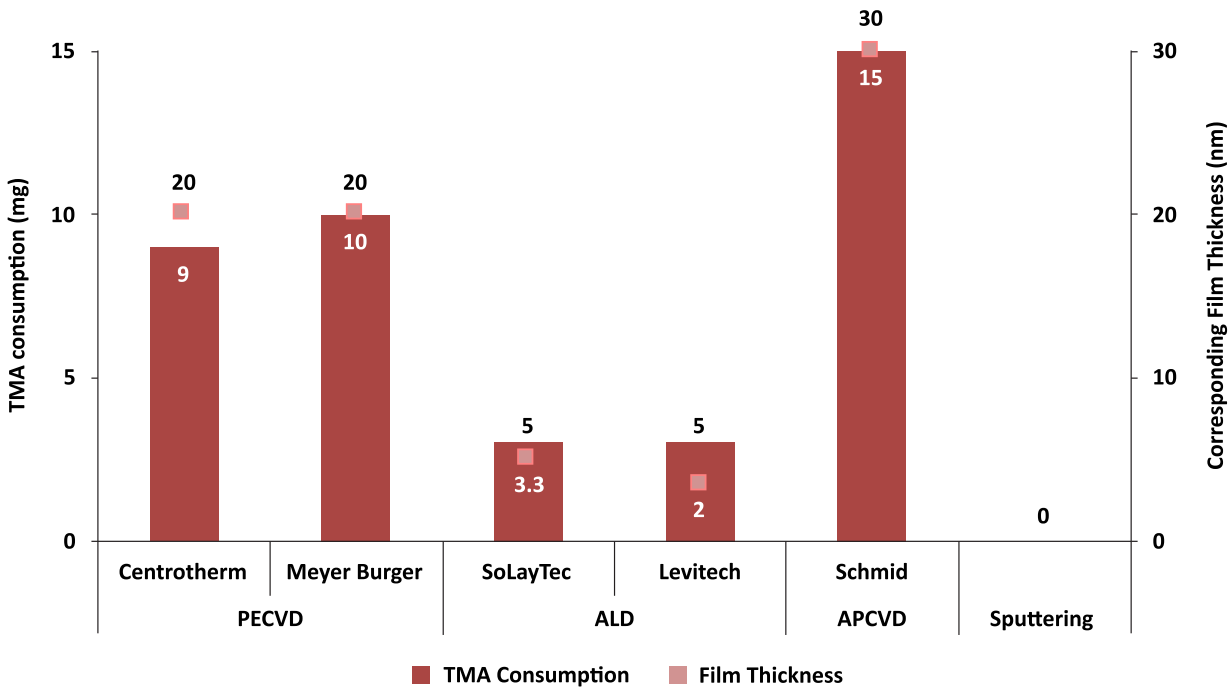
Still, 3 deposition techniques (not considering sputtering) can be commercially employed to deposit this most sought-after rear passivation material. **APCVD**, though supporting higher deposition rates than the other 2, somehow has not entered the main stream. One reason could be when opting for APCVD, the line still requires an additional PECVD system for adding the capping layer. This limitation is also applicable for ALD, but the films deposited with ALD are considered to result in best passivation quality. This might partly compensate for the additional system requirement. Overall, the choice for deposition technologies in commercial production narrows down to **PECVD** and **ALD**. Among the duo, PECVD has certainly outnumbered its rival in terms of its followers. The process comes with

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undeniable advantages - first, every cell manufacturer is well versed in using the technique for silicon nitride deposition on the sunny side. Even more important is PECVD's ability to deposit both aluminum oxide and silicon nitride in one system, reducing further investment to implement PERC. With PECVD technology having a large installed base originating from front passivation, in principle these cell manufacturers can easily upgrade to aluminum oxide from their silicon nitride process. These advantages are paving the path for PECVD to spread its roots deeper into the market.

TMA consumption: However, ALD excels when looking at processing costs. One of the key cost drivers of aluminum oxide deposition is TMA consumption - and ALD tools have a low TMA consumption. To deposit a 5 nm film, SoLayTec's tool consumes about 3.3 mg of TMA per wafer, while Levitech's systems consumes about 2 mg. SoLayTec claims that annual savings from TMA consumption alone would account to 100,000 Euros with its tool over PECVD. One reason for this low consumption is also due to the fact that relatively thinner films are sufficient when deposited with ALD over PECVD. Centrotherm's system has a TMA consumption of 9 mg/wafer, while Meyer Burger's tool requires 10 mg (see graph).

TMA Consumption for Different Aluminum Oxide Deposition Technologies



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ALD reduces TMA needs: ALD technology comes with the lowest TMA consumption at about 3 mg per wafer, followed by PECVD between 9 to 10, while APCVD has the highest TMA usage at 15 mg per wafer.

Uptime: Equipment uptime is another important operational aspect that indirectly contributes to manufacturing costs. High system uptime is another advantage for ALD, emphasizes SoLayTec. Its co-founder Roger Görtzen says that his company's systems currently have an uptime of 94%, with a target to reach 97% in the coming years. However, while inline PECVD systems generally are known to have a lower uptime, the deposition tools from Meyer Burger, a classic example of inline tools, have an

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uptime of 93% - and that is very close to SoLayTec's products. Still, this is lower than for tube PECVD systems: Centrotherm claims its tube furnace products reach up to 97%.

In summary, ALD offers the best quality and highest TMA efficiency, while PECVD scores high with its long experience in PV manufacturing and its ability to deposit both aluminum oxide and silicon nitride in one system, reducing further investment to implement PERC cell technology (see table).

Comparison of Technologies for Aluminum Oxide Deposition

Deposition Method	Commercially Available	Film Stable During Firing Process	Incl. Consecutive Depostion of Capping Layer	Overall Passivation Quality	Experience in PV manufacturing	TMA Consumption Efficiency	Throughput per tool
ALD	✓✓✓	✓✓✓	✖	✓✓✓	✓	✓✓✓	✓
PECVD	✓✓✓	✓✓✓	✓	✓✓	✓✓✓	✓✓	✓✓
APCVD	✓✓✓	✓✓✓	✖	✓✓	✓	✓**	✓✓✓
Sputtering	✖	✓✓	✖	✓	✓	0**	✓

Legend: ✓✓✓ Very Good; ✓✓ Good; ✓ Acceptable; ✖ Unacceptable

Notes: *Single source; **Does not use TMA, but employs less expensive aluminum targets; ***Other precursors are also possible

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While the quality and TMA efficiency is the highest for ALD technology, PECVD scores high with its long experience in PV manufacturing and its ability to deposit both aluminum oxide and silicon nitride in one system, reducing further investment to implement PERC.

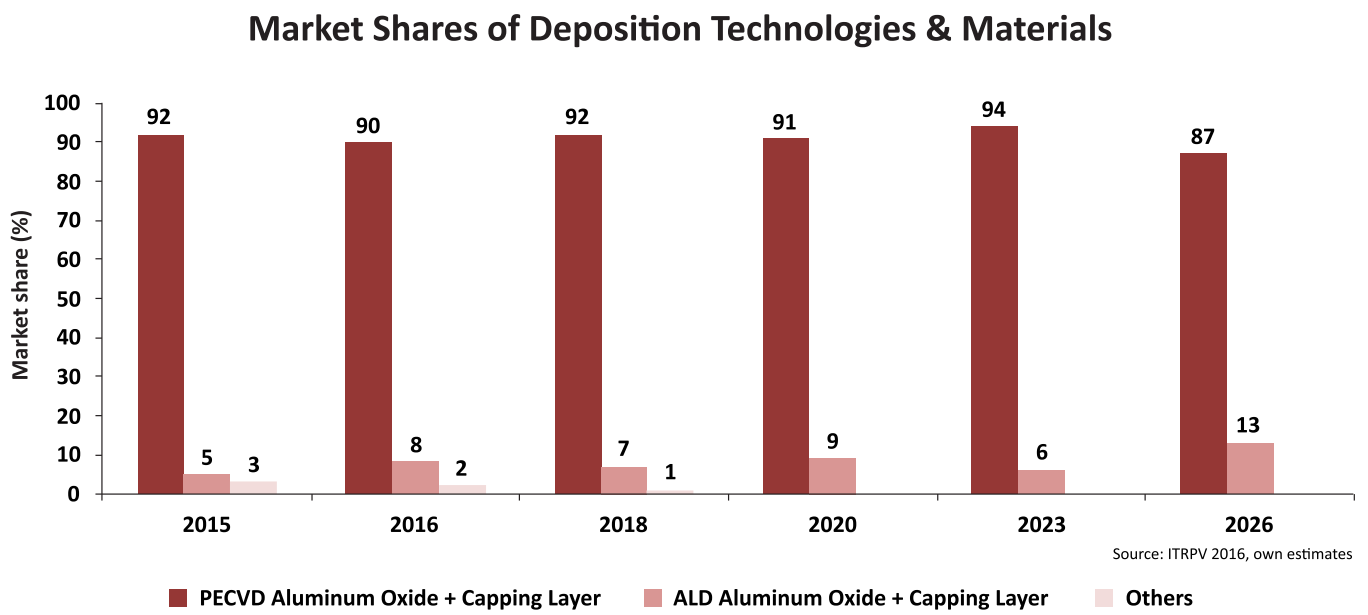
2.2.4.3 Market Shares of Deposition Technologies & Materials

THIS is also reflected in the latest ITRPV forecast. According to the 2016 roadmap, PECVD deposited aluminum oxide retained its dominance with 92% market share in 2015 and will attain 94% in 2023 with small ups and downs in-between. ALD deposited aluminum oxide is expected to gain in long run. From the share of 5% in 2015 the technology is expected reach 13% in 2026, when PECVD is anticipated to drop to 87%.

PECVD suppliers told us that ALD has a lower presence than depicted in the ITRPV, while ALD tool suppliers such as Levitech and SoLayTec envision a higher market share for their technology on account of better quality of the films deposited with their method. The aluminum oxide films deposited with ALD are generally considered to be best in class when looking at overall passivation properties. Levitech claims 0.3% higher absolute efficiency with the films deposited using its systems. However, Thorsten Dullweber, head of the industrial solar cell unit at ISFH, says his institute has made an extensive comparison of various passivation configurations and found that the properties of an aluminum oxide / silicon nitride stack are independent from the deposition process, no matter if ALD or PECVD equipment is used. And even if there is a slight difference, it is not so significant that it results in considerable differences in efficiency. Paul Basore, a solar industry veteran, currently working as a principal engineer for R&D planning and evaluation at the US National Renewable Energy Laboratory

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(NREL), backs Dullweber's findings. He believes ALD technology cannot win in the current first commercialization phase, even if it shows higher efficiencies in lab or pilot lines. That's because there are a lot of other things that need to be taken into account in manufacturing, such as throughput, yield, space, footprint, cost of equipment. Considering that cell makers usually prefer to play safe, the first step towards PERC would be PECVD, says Basore. If there is a second investment phase, ALD certainly has chance to gain market share. PV manufacturers are cost cautious - and ALD might score in this aspect due to lower maintenance and operational costs (see graph).



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Market leader, PECVD: According to the 7th edition of ITRPV, PECVD is and will remain the dominating technology of choice for rear passivation with market shares above 90% until 2023, whereas ALD will gain in the long run from 5% in 2015 to 13% in the next 10 years.

2.2.5 Methods for Opening the Stack

Rear surface engineering is quite different from the front side. Thus the aftermath of applying rear passivation is also different. The classic metallic aluminum paste, applied with standard cells as BSF, cannot be used for PERC, as it deteriorates the entire passivation scheme. Still, aluminum has to establish a contact with the silicon under the passivation layer to form rear contacts. Thus, not only a new set of paste system is required, but an active path has to be laid for aluminum to reach the silicon. A common method is to remove the passivation stack for certain areas. This can be realized in many ways.

2.2.5.1 Etching Paste

ONE way to remove the passivation stack is to use etching paste. This is usually a rather expensive affair; as such a setup requires adding three more tools to the line - a printer to apply paste, a dryer to trigger etching, and a wet bench to clean the process debris from the wafer surface.

2.2.5.2 Laser Technology

THE simplest approach to open the stack is to use laser technology. As lasers have been used in solar

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for many jobs (e.g. thin-film module structuring, edge isolation), there is a huge variety of laser technologies available. The majority of the industry is focusing on laser based ablation. As for the opening of the rear passivation stack, nearly every known laser solution provider is offering products, including laser specialists InnoLas Solutions, Rofin, 3D-Micromac, but also solar equipment suppliers, like Schmid or Manz. However, the laser know-how has spread to an extent that these well known companies increasingly have to compete with low-cost Asian suppliers. While the passivation equipment is generally imported from Europe, the laser tools are sourced locally. According to Centrotherm's Haase, cell makers have preferred suppliers and increasingly they come from Asia.

On the other hand, some cell makers, especially technology leaders, like Sino-American Silicon Products (SAS) subsidiary Sunrise Global, are still preferring advanced products from Western laser system suppliers. During the EU PVSEC conference in September 2015, Germany's InnoLas bagged an order for 5 laser tools from Sunrise Global, in addition to the order the laser expert received in 2013. That has made InnoLas, the exclusive supplier of laser machines for SAS' 800 MW PERC capacity, according to the press release.

According to Ernst Hartmannsgruber, marketing and sales director at InnoLas, the important aspects when choosing a laser system are low cost, high lifetime of components and high throughput. Key for a good product is that the laser system supplier chooses the right type of laser source - it could be nanosecond or picosecond laser. Manz as well as InnoLas, for example, are offering systems based on nanosecond laser sources. According to Hartmannsgruber, such a laser source is not only cost effective - regarding both capital expenditure and operational costs, a side effect of using such laser results in a slight surface damage, which complements the PERC process. This surface damage on the wafer surface as a result of laser patterning eases alloying of aluminum with silicon, which enhances the effectiveness of the rear contact, says Hartmannsgruber. Innolas' says its ILS-TT keeps maintenance costs at less than 20,000 Euros per year by using components with a high lifespan, especially the laser source that lasts for 4 to 5 years. The system has a rated throughput of 3,600 wafers per hour, at par to the typical deposition system of the PERC processing line. On top, ILS-TT also supports complex patterning, such as dotted and dashed patterning, which are under evaluation to improve the performance of PERC processing.

After ablating the rear passivation stack with lasers, a special aluminum and busbar paste are applied and all contacts are formed during the co-firing step using the existing firing furnace in the line.

2.2.5.3 Laser Fired Contacts

ALTERNATELY, Fraunhofer ISE has developed an innovative approach called Laser Fired Contacts (LFC), in which the laser is used to ablate the rear passivation stack, while the metallic aluminum is sintered simultaneously. But the approach, which was published by ISE in 2002 in research magazine Progress in Photovoltaics (*Laser-Fired Rear Contacts for Crystalline Silicon Solar Cells. Authors: E. Schneiderlöchner et al.*), has not found any followers among commercial cell producers for various reasons. Fraunhofer ISE owns the intellectual property, so the process could not be accessed free of charge. On the technical front, LFC was introduced at a time, when no suitable aluminum pastes were available. It was mainly intended for aluminum deposited with PVD to realize a good local BSF. But once such paste was on hand, the laser contact opening process resulted in a better BSF. These two factors went in favor of the laser opening process. And since then rapid paste developments have allowed an even faster pace in this direction. As a result, laser contact opening is by far the predominant method employed for opening the rear passivation stack in most of the current PERC production lines.

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2.3 Rear Polishing

WHILE applying rear passivation and ablating the stack for metallization are two important prerequisites for PERC cells, polishing the rear surface is equally important. The reason for etching away the textured surface is that the random pyramid-like surface exhibits a higher degree of recombination compared to a polished surface. One obvious reason is that texturing increases the surface area and also the dangling bonds. Especially when PECVD is used for deposition, the coverage of the passivation layer is better on a planar surface. As the cell's rear side does not actively take part in light absorption and is not involved in direct light trapping, there is no harm in removing the textured surface. And there is an even more fundamental reason - following traditional diffusion, the wafer is doped on either side, unless the rear surface is masked explicitly or single side diffusion is realized in a belt furnace. If the phosphorus is present on the rear side, it has to be removed.

To accomplish rear polishing, no special process or tool setup is required, unless laser systems are used for edge isolation. Just a change in chemistry is required in the wet benches that are used for junction separation. This process chemistry can be intensified to attain the required surface roughness.

The degree of etching might also depend on the process employed to deposit the dielectric layer. For example, ALD facilitates very good step coverage and may not require an active polishing for the passivation purpose, as promoted by Levitech. But in a normal chemical rear emitter and PSG removal step, 1 to 2 µm is anyway removed, and the process can be intensified to attain the required roughness. A report (*How Much Rear Side Polishing Is Required? A Study on The Impact Of Rear Side Polishing In PERC Solar Cells. Authors: E. Corniaglotti et al.*) published at the 27th EU PVSEC, reveals moderate polishing - corresponding to around 5 to 6 µm of etching - is required in order to maximize cell performance. At the same time, making the surface very smooth could be harmful, besides the process would not make economic sense. While surface recombination greatly benefits from polishing, light trapping and contact formation favor a rough surface. According to the above mentioned technical paper, a surface roughness(Ra) range of 300 to 500 nm is optimal. In other words, you have to etch enough to get rid of the phosphorus and pyramid peaks, but at the same time retain the textured surface to benefit from better light management and contact formation.

2.4 Metallization - Special Pastes Required for PERC

ONE of the big advantages of PERC architecture is that it allows staying with time-tested screen printing for metallization. However, some changes are inevitable when it comes to process consumables - a different paste system is required. The front surface of PERC cells is no different from standard cell structures, typical silver formulations for contacting the standard emitter are sufficient. But the rear surface, featuring an additional passivation scheme, needs special attention.

As for the pastes, special rear tabbing and BSF pastes are required, with the latter being more critical. The challenge here is to establish a contact to the silicon, while the aluminum formulation must refrain from causing any damage to the passivation layer beneath. It's like meeting two contrasting requirements. A suitable aluminum paste does not react on those areas where it covers the passivation layer, but at the same time it establishes contacts at areas opened with lasers to create a local BSF. These aluminum pastes are typically non-fire-through products.

A non-reactive rear tabbing silver paste is required as well. The attributes for such pastes are twofold: It should not fire through the passivation layer and it should exhibit good adhesion and solderability.

The leading paste suppliers are offering different ranges of paste formulations. American company **DuPont**, for example, has a complete PERC package with 3 pastes. Introduced in 2015, the PV76x is the latest and designed to contact the front surface, especially for lightly doped emitters; PV56x is offered

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for rear tabbing applications. The PV36x is a product designed to form the local BSF, according to DuPont, it was the first produced in the market for this purpose, introduced in 2011. In general, DuPont is not offering standard aluminum pastes anymore, which it considers a commodity. But in an effort to provide a total solution for PERC cells, the company continues the further development of special local BSF pastes. The PV76x, in addition to providing a good front contact, is designed to be co-processed with PV36x and allows firing at about 50 ^{o}C lower temperature, which minimizes the damage and voids in the passivation layer. According to DuPont, the paste results in an efficiency advantage of 0.15%, and an undisclosed customer using this paste has recently demonstrated an efficiency of 21.5% for monocrystalline PERC cells with standard screen printing in mass production. The product is also used for multicrystalline cells in this area - according to a press release from October 2015, REC, one of the largest PERC cell manufacturers, uses the PV76x paste for its PERC modules.

Silver paste market leader **Heraeus**' product was used for an even slightly higher efficient cell - SolarWorld announced a 21.7% record cell in 2015. The German company supplied the silver pastes for the front side, however, it does not offer aluminum pastes. Heraeus also considers aluminum pastes commodity products, even including pastes for the local BSF. It has been focusing on silver formulations, even though the company got its hands on know-how of aluminum paste after acquiring Ferro's solar business. But Heraeus' Head of Global Business Development Arno Stassen considers the price premium attracted by this so-called specialty paste not worth the investment effort, so the company decided to stay away from this non-precious metal pastes segment.

Heraeus' PERC portfolio includes two dedicated products - SOL325, the non-contacting rear busbar paste and 9621B for the front. The SOL325 is offered in two variants - with A and B suffix - and its differentiating factors are their viscosity and the solid content. The SOL325A comes with a viscosity range of 50 to 120 kcps and solid loading of 59.5% (+/-1%), while the SOL325B has higher solid loading of 67.3% (+/-1.5%) with a slightly lower viscosity range of 50 to 110 kcps. The latter, due to its higher silver content exhibits lower resistivity. According to Heraeus, the SOL325 series has demonstrated



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efficiencies greater than 20% by reducing the recombination of charge carriers and lower grid resistivity, while providing good adhesion.

When it comes to front pastes, Heraeus' Stassen says that most of its front pastes can also be used for PERC, but the SOL9621B is a dedicated model. This product series is said to have demonstrated a gain of 0.1% absolute over its predecessor on a 110 ohm/sq emitter of multicrystalline cells. According to a product data sheet, the SOL9621 shows 52% reduction in contact resistance, which helps in boosting the cell's Voc by 1 to 2 mV. Heraeus is also promoting its latest SOL9631 for PERC applications. This is a heavy metal free front-contact formulation that can be printed through a 30 to 45 µm screen opening and which - at 3.13 N - has almost double the adhesion of the 9621 series. Heraeus is offering the SOL9631 in several variations in order to suit specific customer needs - and fine-tuning it for PERC applications is one such possibility.



World record holder: At the time, this report was published (Feb. 2016) Trina Solar was holding the record efficiencies for both mono- and multi PERC cells. Shown is Trina's PERC multicrystalline solar module.

As for PERC, there is a clear differentiation between mono and multicrystalline, but pastes makers seem to be untouched by this. The current crop of products is generic to both crystalline silicon class variants. According to Heraeus, certain adaptation of paste formulation is anyway required for every large customer and tweaking for mono and multi is already an integral part. This may change in 2 to 3 years, when there could be a clear differentiation in processing is established between multi and mono, says DuPont's Global Technology Director Homer Antoniadis. Other paste suppliers are developing formulations for rear tab and local BSF applications specific for PERC as well.

2.5 Production Equipment Solutions for PERC Processing

IN addition to selling specific tools for PERC processing, some equipment makers are also offering package solutions, which includes everything needed to produce a PERC cell, sometimes even with efficiency guarantees. The top cell manufacturers with their own R&D facilities may not be interested in such options, but tier 2 or tier 3 cell makers with limited research resources and companies in developing markets may opt for such package solutions. While ALD machine suppliers offer complete solutions for rear passivation, major PECVD tool makers Centrotherm, Manz, Meyer Burger and Singulus are providing package solutions for PERC - both for new lines or upgrades for existing lines. We have briefly summarized the PERC packages of the leading equipment manufacturers for both PECVD and ALD-based tools:

2.5.1 PECVD-based Packages

Centrotherm was the first of the big equipment makers offering a PERC cell solution with the name Centaurus. More than a package, the solution was a very clever strategy to sell a low-cost upgrade for unused installed equipment back during the solar recession period when cell manufacturers did not have money to spend on new equipment. Centrotherm bet on silicon oxynitride as passivation

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material and wrapped the selective emitter formation into the package that was mainly intended for monocrystalline wafers. At the time, the company was very successful with its low-cost retrofit solution. But the technology is known to have also hurdles - rear polishing involves removing 8 to 10 mm and required thick capping layer of up to 200 mm. Moreover, rear metallization is not easy. These reasons likely have lead even early adopters of the technology, such as SolarWorld, to opt for aluminum oxide. Very recently, also Centrotherm has started offering an aluminum oxide upgrade to its PECVD systems as well. The package is advertised with an efficiency potential of 20.8% on monocrystalline substrates.

Manz is offering a completely homegrown PERC upgrade package. The solution also includes wet-chemical benches for rear polishing, PECVD systems for deposition of dielectric films and laser ablation too. All three tools are developed in-house. The process is applicable for both mono and multicrystalline wafers. The PECVD tools of the company have a rated throughput of 1,200 wafers per hour and the laser tool comes with a capacity of 2,400 wafers per hour. The wet-chemical bench has an hourly throughput of 4,800 wafers. That means the optimal setup to complete utilization of each production tool would be one rear polishing tool feeding 4 PECVD machines and followed by 2 laser scribers. However, the most important parts of the solution are PECVD and laser systems, which Manz emphasizes are tools with a small footprint, making them suitable for upgrading existing production lines. If required, Manz is also offering necessary automation for these tools. The company assures a PERC cell efficiency of 20.6%.

Meyer Burger is offering a PERC upgrade package. Its solution includes PECVD-deposited aluminum oxide capped with silicon nitride. Deposition is realized with its MAiA platform on rear side and laser ablation of the passivation stack. The process is named MB-PERC, and comes with a guaranteed cell efficiency greater than 20% on p-type monocrystalline wafers. Meyer Burger claims that the upgrade of its PERC technology results in cost reduction of 5 Euro cents per watt, including module and BOS costs. The heart of this line, the rear passivation layer deposition system, has a rated throughput of 3,200 to 3,500 wafers per hour, which according to the company synchronizes with other tools in the line.

Schmid Group was one of the early equipment maker that ventured into PERC technology. Back in 2011, the company in cooperation with then still active cell manufacturer Schott Solar proved that efficiency over 20% can be attained with monocrystalline wafers by implementing PERC architecture using an industry-proven processes. Already in 2012, Schmid started offering a turnkey solution, which involves APCVD instead of PECVD for depositing aluminum oxide. Schmid has also developed a PECVD platform for depositing the silicon nitride capping. For several reasons, one of which was the recent PV industry downturn, Schmid's solution has not won many customers. In the meantime, Schmid has shifted its focus to other advanced cell concepts, like bifacial, n-PERT and IBC. The company even discontinued its PECVD solution. But it is still very active in the PERC segment through the supply of its wet-chemical benches. In the case of requests for package solutions, Schmid teams up with Meyer Burger for PECVD systems.

Singulus calls its solution PERCEUS. The package consists of a single side polishing tool of the company, an ICP-plasma assisted PECVD tool to deposit the aluminum oxide and the silicon nitride stack, and a laser system from an undisclosed partner. Singulus says that implementing its PERC solution can lead to cell level efficiencies exceeding 22%. That seems very ambitious but when contacted Singulus didn't want to provide any details. The equipment maker presented a paper (*Implementation and Optimization of an Industrial mc-Si PERC Process for Mass Production. Authors: J. Denafas et al.*) at the EU PVSEC Conference in September 2015 in Hamburg, saying that a stable efficiency gain of up to 1% absolute could be achieved over the Al-BSF baseline using a laser edge isolation process with multicrystalline wafers of various quality and origin. The best cell efficiency reported in the paper was 18.7%.

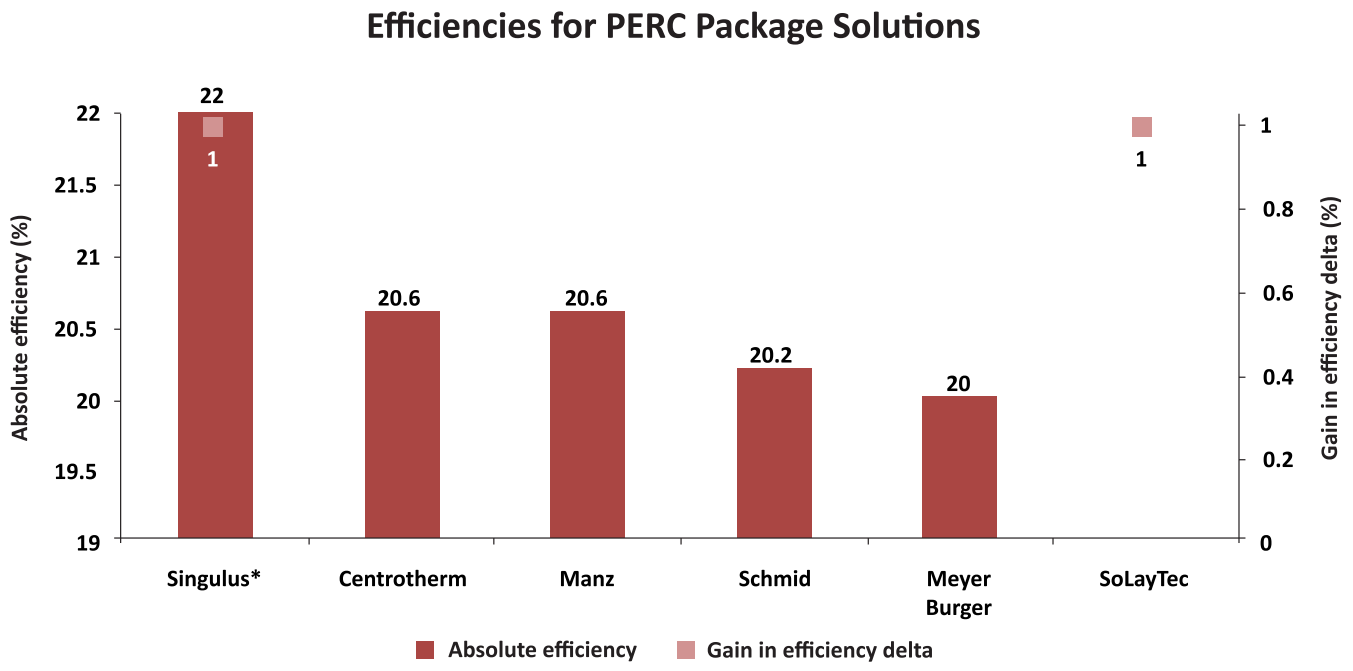
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2.5.2 ALD-based Equipment Solutions

UNLIKE the PECVD tools from above mentioned companies, which deposit aluminum oxide capped with silicon nitride in one go, ALD equipment only deposits the aluminum oxide layer. It relies on PECVD only for capping. Thus some ALD suppliers are offering integrated solutions for the entire rear passivation stack.

This has been a natural progression for **SoLayTec**. The Dutch company was owned by RENA, which sold SoLayTec's shares to US-based Amtech Systems at the end of 2014 as part of a restructuring that followed an insolvency filing. As a result of this new ownership, SoLayTec is now teaming up with PECVD supplier Tempress, another subsidiary of Amtech. The later designed a special recipe that involves annealing after aluminum oxide deposition, but before putting the capping layer. In this step, aluminum oxide is activated along with hydrogen out gassing of the film. SoLayTec claims, the additional annealing step improves efficiency. The ideal configuration would be the installation of two ALD systems that supply three PECVD direct plasma tube furnaces, each with a capacity of 2,200 wafers per hour resulting in an average net throughput of 6,400 wafers per hour. SoLayTec is also willing to cooperate with other tool vendors to offer a one stop solution with a guarantee to boost the cell efficiency by about 1% absolute for monocrystalline and 0.6% absolute for multicrystalline cells. The actual values depend on the baseline process.

Levitech is cooperating with an undisclosed PECVD supplier, which seems to be the only step the company took towards a package solution, but it didn't provide any details (see graph).



Notes: * Though not direclty assuring a level of 22% the PERCEUS page of Singulus' website claims "With the integration of three additional production steps into existing production lines, PERC cells with efficiencies over 22% can be made.

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Package with performance assurances: Although the efficiency Meyer Burger's assures for PERC cells made with its package line appears to be low, the company is certainly the market leader in rear passivation layer deposition tools segment. So far, cell makers usually haven't purchased PERC package lines but rather single tools.

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3. Recent PERC Cell Efficiency Records - from Companies and Institutes

IT is evident from the above sections that switching from standard to PERC technology is industrially feasible - the equipment is available, the materials are on offer, and so is the process. Another evidence for the industrial viability of the technology is that the best efficiencies for industrially feasible PERC technology have been attained by PV manufactures rather than research institutes. At the publication date of the study (March 15, 2016), the PERC cell efficiency record at 22.13% is being held by Trina Solar. We have summarized the recent PERC cell efficiency records from companies for both mono- and multicrystalline PERC cells.

3.1 Monocrystalline PERC Cell efficiencies

FOLLOWING a chronological order, **Suntech** announced in 2012 that its PERC cells attained a 20.3% efficiency. In 2012, **Sunrise Global** achieved average production efficiency of 20.2% using industrial processes and announced in February 2013 an increase to 20.3%. The Taiwanese company used aluminum oxide deposited with PECVD equipment. Sunrise is not only one of the earliest adopters of PERC technology for mass production, it is also one of the largest PERC cell manufacturers. Today, **Sunrise** produces cells with around 20.7% efficiency in average, while peak performance exceeds 21%. When using high quality wafers, its average efficiencies are 21.2%, Sunrise says. Also in 2012, **Schott Solar** reached 21% using monocrystalline wafers; the German company licensed its technology to Schmid Group. In late 2014, **Trina** announced 21.4%. The announcements on efficiency numbers strongly increased over the course of 2015. In May 2015, **Suntech** said it reached 20.5% average efficiency in volume production, followed by **SolarWorld**'s21.7% announcement in July, the highest for a commercial-size PERC cell at that time. Though **NSP** from Taiwan sent out a press release in October that its monocrystalline PERC cell reached 21.1% efficiency, **SolarWorld** continued to hold the world record until **Trina** took over in December 2015. The Chinese integrated PV module maker produce a 22.13%efficient PERC cell. At the beginning of January 2016, **Gintech** said it attained 21.44%, which at that time meant at third place in the PERC cell peak efficiency ranking. Though **SolarWorld** reported an improvement for its peak PERC cell performance in mid January 2016, resulting in an efficiency of 22%, the ranking has not changed.

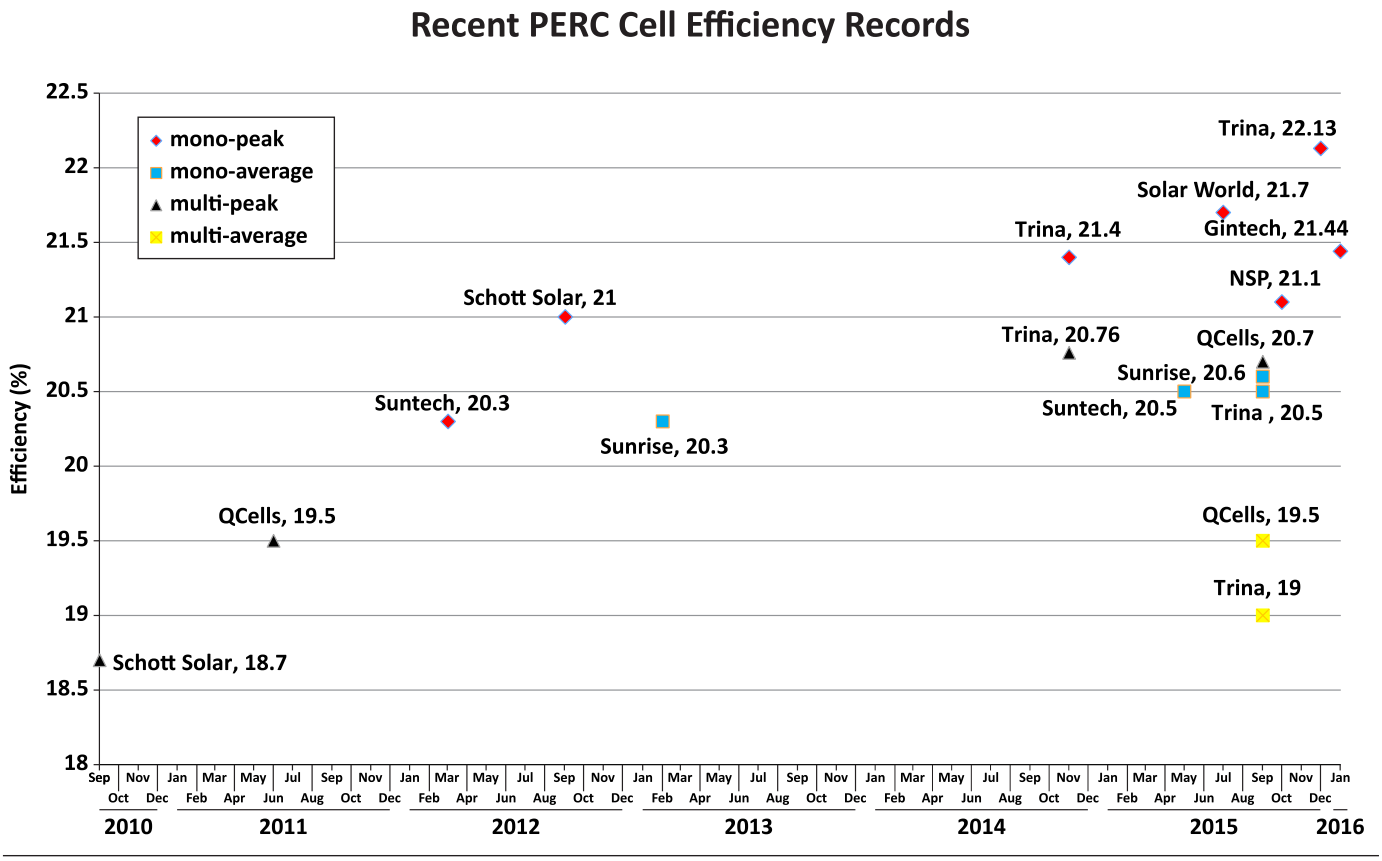
3.2 Multicrystalline PERC Efficiencies

THERE has been less efforts in developing multicrystalline PERC cells. Multicrystalline cell technology, the workhorse of the solar industry also have high efficiencies (which in recent years dramatically increased through improvements in crystallization technology), but foremost these cells have to be manufactured at very low cost to offer them at competitive prices for utility-scale solar power plants. However, Schott was the first company to start the hunt for records, attaining 18.7% in 2010. **QCells** came next, reporting 19.5% in 2011 - that's a level it is now reaching in production. At the same time, the lab level performance went up to 20.7%. In 2014, JA Solar attained a 20% peak conversion efficiency. After **Trina** hit 20.76% in November 2014, only one year later, the Chinese company announced a 21.25% PERC cell on a 156 x 156 mm multicrystalline silicon wafer. That's the first time a multicrystalline solar cell was produced that exceeds the 21% efficiency level. Trina says its average multicrystalline cell production efficiency is around 19% today (see graph on page 33).

3.3 Future Development for PERC Cell Efficiencies

USUALLY it takes quite some time to translate cell records into day-to-day cost-competitive production levels, which is the most important criterion for any technology. Equipment maker Semco sees a PV fab with more than 500 MW capacity, averaging efficiency of 20.8% for best in class cells and the majority ranging between 20.1% to 20.4%today. SoLayTec says, 20.7% average is soon in reach in China, with the best efficiencies reaching over 21%.However, when you look at Sunrise Global in

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Time for records: PV companies are increasingly competing for PERC record efficiencies - there were 9 announcements in 2015 alone. Chinese integrated module maker Trina holds the records for both mono- and multicrystalline silicon PERC cells.

Taiwan, it says it is producing today already at the level SoLayTec is forecasting - as mentioned above, they make monocrystalline cells with around 20.7% efficiency in average and over 21% for top cells.

It is very likely that we will see further PERC efficiency records this year - both for lab and production levels. The German HELENE research project, which is coordinated by SolarWorld, targets 22.5% efficient PERC mono cells by the end of 2017.

As to the question on the efficiency potential of mass-produced PERC cells, a research group lead by ISFH has investigated and modeled that "the continuous developments of industrial-type PERC cells may lead to cell efficiencies beyond 24%. In their paper (*Incremental Efficiency Improvements Of Mass-Produced PERC Cells Up To 24%, Predicted Solely With Continuous Development Of Existing Technologies And Wafer Materials. Authors: B. Min et al.*), which was presented at the 31st EU PVSEC in Hamburg in September 2015, the researchers pointed out that near term improvements of PERC cells will focus on the following key points: advanced emitter structures such as selective emitters, boron-added Al paste for the rear, wafers with 1 ms lifetime, multi wires instead of busbars and 10 µm narrow fingers with high aspect ratios (see graph, page 40).

4. Commercialization & Capacity Estimates

RECORD efficiencies give an indication for the PERC cell leaders, but they do not directly correlate with

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PERC Study Capacity Announcements

Date	Company	Capacity	Type of PERC Addition	Description
09-Mar-15	Meyer Burger / SolarWorld	400 MW	PERC upgrade	Meyer Burger announced that it will supply MAiA tools with a capacity of 400 MW to SolarWorld for upgrading cell lines of an existing factory in Germany.
28-Apr-15	Manz		PERC upgrade	Manz said its order intake for PERC upgrades has exceeded €6 million.
19-May-15	Meyer Burger	2.5 GW	Rear passivation tools order	Meyer Burger received an order for it MAiA systems mainly used for PERC processing from an undisclosed Asian customer. The deal is worth of 38 million CHF to deliver equipment with a capacity of 2.5 GW.
02-Jun-15	Meyer Burger / Lerri Solar		PERC upgrade	Meyer Burger announced it won an order worth of 16.5 million CHF from Lerri Solar Technology to supply its PERC upgrade solution and PV measurement technology.
08-Jun-15	Suntech	1 GW	PERC upgrade	Suntech said it has plans to upgrade to PERC technology eventually with a capacity of 1 GW.
26-Jun-15	Solartech Energy	240 MW	Adding PERC capacity	Solartech Energy Corp announced its plans to expand its PERC polycrystalline cells production capacity to 240 MW by the end of September from the current 60 MW.
07-Jul-15	Lerri Solar	2 GW	New factory with PERC	Lerri Solar, a division of wafersmaker Longi, expressed its intension to invest 2.79 billion RMB in establishing 2 GW of monocrystalline PERC cells production factory in China in the coming 3 years.
29-Oct-15	Innolas/Sunrise Global	450 MW	New factory with PERC	InnoLas has bagged an order for 5 laser systems from Sunrise Global supporting about 450 MW. With this Sunrise Global has a close to 1 GW installed capacity
12-Nov-15	Zhongli Talesun	500 MW	Production start at new factory	The entire capacity of 500 MW at Zhongli Talesun's new production facility in Thailand that came into operation in November 2015 is completely PERC capable.
19-Nov-15	Canadian Solar	400 MW	Production start at new factory	Canadian Solar announced in its third quarter 2015 update that PERC production rollout has begun in third quarter of 2015, which will be gradually ramped up to 400 MW.
19-Nov-15	SolarWorld	800 MW		According to SolarWorld's second quarter interim report, over the course of the second half of 2015, the company will have a PERC capacity of more than 800 MW.
30-Nov-15	NSP	500 MW	Capacity reshuffle	NSP announced adjusting allocation of its domestic and overseas production capacities through shifting a portion of capacity from Taiwan to Malaysia and China and adding capacity in Malaysia. After this reshuffle, NSP's PERC production capacity reaches 500 MW – 400 MW in Taiwan and 100 MW in Malaysia.
28-Jan-16	Meyer Burger		Rear passivation tools order	Meyer Burger announces that a 22 million CHF order also includes supply of MAiA tools for a Asian cell maker

PERC sells: There were plenty of PERC-related announcements from both equipment makers and cell producers in 2015

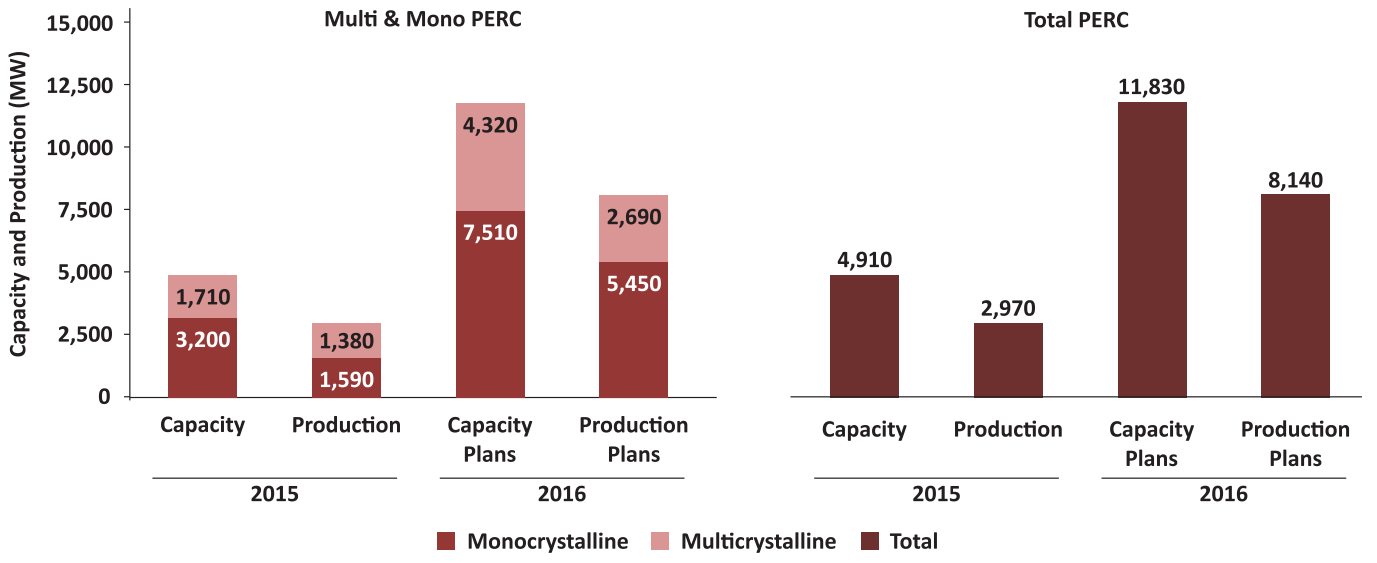
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commercial production. While Sunrise Global from Taiwan, SolarWorld from Germany and Hanwha QCells have been mass producing PERC cells for a few years, the technology made a big splash in trade media when Meyer Burger announced in March 2015 that they received an order for PERC equipment worth 38 million Swiss Francs and equal to 2.5 GW from an undisclosed Asian customer - with delivery and commissioning supposed to take place between Q3/2015 and early 2016, and production start targeted for end of 2015. We have listed the recent public announcements of equipment makers on PERC machine shipments and cell makers that plan to use PERC technology for their production (see table on page 34).

Based on our research with leading scientists and technology experts, PERC equipment and cell manufacturers, we have estimated global production capacities and actual output for 2015 and 2016. According to our research, as of end of 2015, PERC had an installed capacity of 4.9 GW, while about 3 GW was actually produced. However, the technology is supposed to see a real big jump in 2016 - with installed capacity reaching 11.8 GW over the course of the year, resulting in 8.1 GW PERC cells being produced in 2016. While the majority of companies is betting on monocrystalline PERC technology, 2 companies are focusing on the multicrystalline variety. Cell makers - REC and most importantly QCells - will be the main contributors to multicrystalline capacity additions and production in 2016. While last year's mono capacity reached 3.2 GW, multicrystalline was 1.7 GW. The respective production volumes were 1.6 GW for mono and 1.4 GW for multi. In 2016, the installed capacity base for monocrystalline PERC is estimated to reach 7.5 GW, which will result in production of 5.4 MW, while we anticipate 2.7 GW of multicrystalline PERC cells output from an installed manufacturing capacity of 4.3 GW (see graph).

PERC Capacity and Production Estimates 2015 and 2016



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Prime time for PERC: According to our research, PERC really started taking off in 2015 with about 4.9 GW installed capacity, which lead to a production of 3 GW. In 2016, total PERC production capacity is supposed to more than double, while output would grow of close to 3X, indicating more and more companies are moving into commercial production.

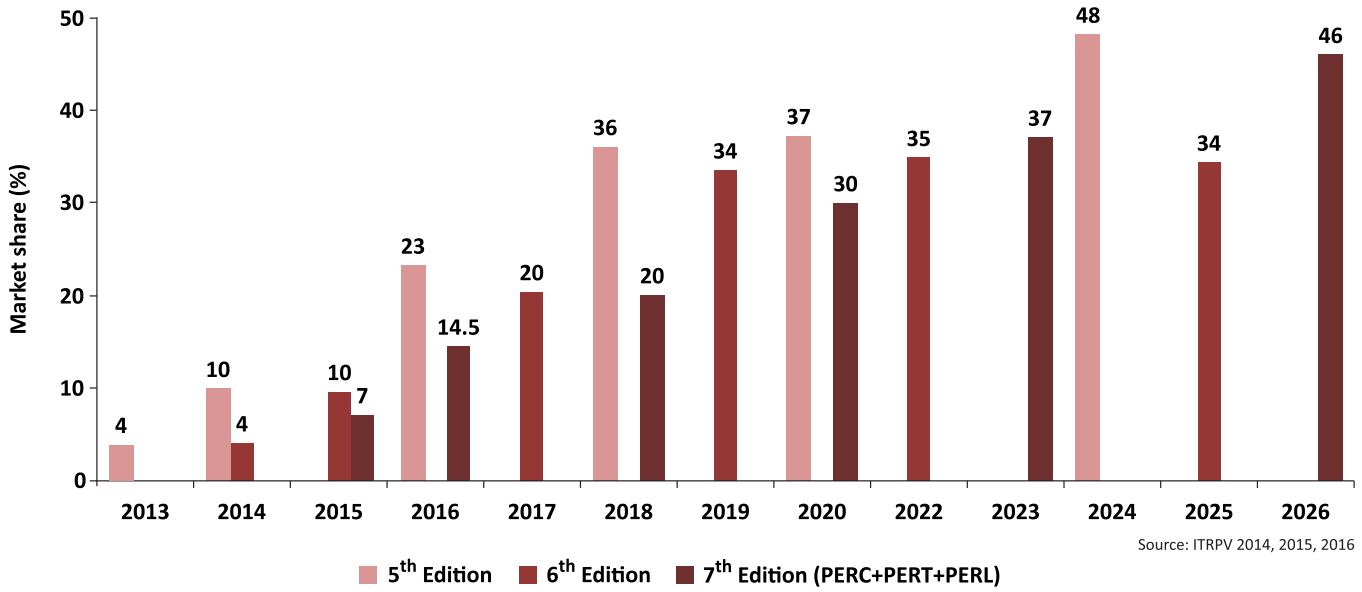
When comparing our research with the PERC capacity estimates from the experts we interviewed, our results are in the middle of the data range (see graph, page 43). We also put our numbers into another perspective and have taken a look at the forecasts of the 7th International Technology Roadmap for Photovoltaic (ITRPV), which was released in mid-March 2016. While ITRPV assumes a

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share of 7% PERC cells for 2015 (down from its 2015 estimate of 10%) and about 14.5% PERC in 2016, our estimates result in a PERC share of 5% in 2015 and nearly 12% in 2016 (when taking IHS demand of 59 GW in 2015 and 69 GW in 2016 into account).

The 7th ITRPV roadmap had expected PERC technology not only to gain about 7% market share in 2015, but forecasts that PERC doubles its presence to 14.5% in 2016. However, the previous roadmap had anticipated to climb from 10% in 2015 to 20%. While the 2014 edition expected PERC to contribute 50% of cell production in 2024, the 2015 study forecasted the market share of PERC to attain 35% share in 2022 but make no significant gain beyond that level. The latest estimate is somewhat blurry, as ITRPV 2016 combines PERC, PERL and PERT technologies, which it anticipates to reach 37% by 2023 - in any case, again another more conservative approach (see graph).

Changing ITRPV Forecasts for PERC Market Shares



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In its 6th edition from 2015, the ITRPV has been still very optimistic on the future of PERC, but has decreased the long-term shares in its forecast compared to the 5th edition, released in 2014.

5. Challenges for PERC

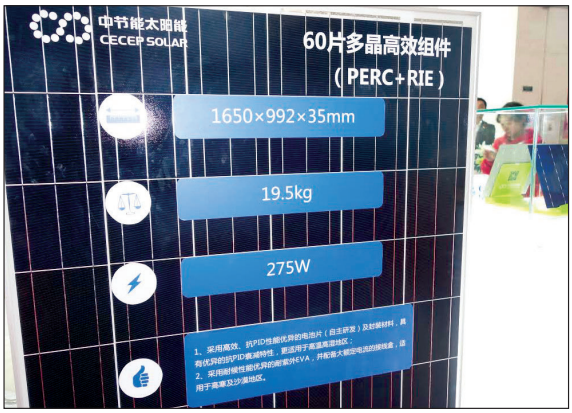
PERC, like any other solar cell technology, also comes with a number of shortcomings, which include:

5.1 Light Induced Degradation

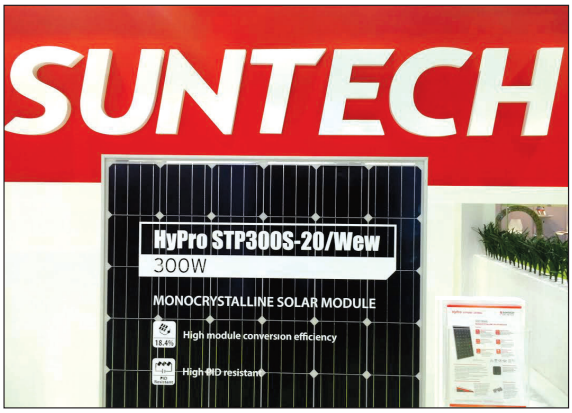
MOST challenges PERC is facing are no big issues, but there is one serious bottleneck - Light Induced Degradation (LID), especially associated with multicrystalline cells. This is the reason why only two companies are producing multi PERC cells on a large scale - Hanwha QCells and REC Solar. But both - belonging to the world's largest PERC cell producers - say they have solved the problem.

The multicrystalline LID bulk phenomenon leads to a severe performance degradation in operating

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All about PERC: Solar modules with PERC cells are increasingly on display at solar trade shows, but the marketing strategies differ quite a bit. While Suntech or REC are not even mentioning that their premium products contain PERC cells, GCL strongly emphasizes this fact, while CECP Solar even showed at a show in Beijing in 2015 a prototype PERC module that was not even commercially available at the time.

Photo credit: © TaiyangNews 2016

conditions, such as longer illuminations and higher operating temperatures. QCells has called this phenomenon Light and elevated Temperature Induced Degradation (LeTID), factoring in the temperature dependence of the degradation.

While most experts agree that the LeTID root cause is not clearly understood, the cause of this degradation is not due to the well-knownLID phenomenon in monocrystalline silicon - formation of a boron-oxygen complex or iron boron pair dissociation. However, the damage can be huge: QCells presented at the 31st EUPVSEC in September 2015 that the LeTID could result in up to 10% degradation in module output power on a time scale of several hundred hours. This research paper evaluated the influence of different parameters on LeTID, such as variation in surface passivation layers and cell dependency on the brick height. QCells' findings indicate that the degradation is a strong silicon material effect, and elevated temperatures accelerate degradation. After reaching the maximum degradation level, there is also a regeneration effect. However, the time span for degradation plus regeneration of thousands of hours is too long to take effect during the warranty period.

It seems that QCells has found a solution in optimizing the cell processing sequence, but the cell maker would not reveal the details. According to NREL's Basore, this effect is closely associated with

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heavier doping. It could be completely avoided by lighter doping, but then the benefits of moving to PERC would diminish as well.

Minimizing the LID would be the optimal solution. It could be avoided by carefully choosing the wafer material, because the bulk quality influences the effect. But that's a rather vague, impractical solution. Appropriate annealing is probably the most suitable way to solve this issue, says Basore. SoLayTec also says that some kind of temperature treatment before firing is a way to at least stabilize LID.

5.2 Durability

Then, the long-term durability of rear surface passivation is not completely known. From an electronic point of view, the structured differs enough from a standard Al-BSF, that opportunities are big enough for things to go wrong over 25 years. Centrotherm's Haase adds to that aluminum oxide is not only a new material, the film is deposited from a liquid precursor, which is not the case with other dielectrics used for the cell. Thus, reliability needs to be looked at very carefully.

5.3 Cost

But if financing works, there are no show stoppers for PERC, Meyer Burger's Erfurt adds. Basore estimates that banks will initially fund investments in rather small capacities, but would put more money as every year goes by. Growth will be gradual, if something goes seriously wrong, it would stop. Additional capital expenditure is also a concern, says Meyer Burger's Erfurt (who we interviewed just before he started with Meyer Burger).

The **capital investment** actually depends on the line configuration. Considering a PERC upgrade for a 100 MW cell production, which already has a chemical edge isolation wet bench in place, the rear polishing tool can be excluded from the capex estimation. A 100 MW PERC line requires one typical laser system that is priced roughly between 1 to 2 million Euros, depending on brand and quality. A PECVD system that deposits a complete rear passivation stack of aluminum oxide capped with silicon nitride with similar capacity is priced at about 1.5 million Euros. This accounts to capital expenditure of about 2.5 to 3.5 million Euros for a 100 MW line upgrade based on a PECVD based rear passivation scheme. In case a cell maker prefers ALD, the laser cost remains the same. An ALD system with a capacity of 100 MW has a price tag of about 1.2 million Euros. Such a line also requires an additional PECVD system for silicon nitride capping, which costs about 1 million Euros. That means the PERC upgrade involving ALD rear passivation configuration attracts an investment of about 3.2 to 4.2 million Euros. A new 100 MW production line with PERC processing ability mostly based on PECVD costs about 10 to 12 million Euros.

When it comes to **operational costs**, the TMA price is the key driver. In fact, the very high price of TMA is one of the main concerns associated with adaptation of ALD into PV processing. Chemical suppliers started offering less pure TMA called solar grade TMA for nearly 10% of the price of semiconductor grade TMA. A 2010 technical paper from Eindhoven University of Technology (*Recent Progress in the Development and Understanding of Silicon Surface Passivation by Aluminum Oxide for Photovoltaic, Author: G. Dingemans, et al*) has evaluated the influence of the precursor purity and found out no significant difference observed in passivation properties for the ALD deposited layers using solar grade and semiconductor grade TMA precursors. According to another technical paper form IMEC (*Integration Of Spatial ALD Aluminum Oxide For Rear Side Passivation Of P-Type PERC/PERL Solar Cells, Authors: E. Cornagliotti et al.*), in 2013, when the paper was published, electronic grade TMA cost 6,000 Euros per kg, while the solar grade variant of the chemical was offered for 600 Euros per kg. Today the price of TMA is about 750 Euros per kg. For depositing the aluminum oxide film using PECVD, which requires about 10 mg of TMA, the precursor

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consumption accounts for about 0.75 Euro cents per wafer, whereas ALD requires only about 2 to 3 mg, resulting in processing costs of around 0.225 Euro cents per wafer. APCVD has the highest cost associated with precursor consumption - it needs around 15 mg of TMA, which translates into processing costs of 1.12 Euro cents per wafer.

5.4 Operations & Performance

THERE could be **operational issues** due to stability of the production tools in case they do not run as expected, says Centrotherm's Haase. Then there is the process complexity, especially the laser ablation step, says ISC Konstanz' Kopecek. And when thinking about multicrystalline PERC, you can argue about the additional cost for annealing, as Meyer Burger's Erfurt does. Instead of investing in development activities for a PERC line suitable for multicrystalline, shifting the process to mono then adapt PERC would be more straightforward, in his view. It would require only a switch from acidic to alkaline texturing.

Ralf Preu, Head of Production Technology at Fraunhofer ISE, emphasizes that the **efficiency delta** from PERC to standard cells needs to be at least about 0.8 to 1% absolute in order to justify the additional expenses and efforts. While standard technology is approaching 20% efficiency, PERC needs to attain production peak efficiencies of 21%+ in 2016, while the average efficiency could be 1% to 2% relatively less. According to Kopecek, the major shortcoming is the current sales metric, which is watt peak; he believes that PERC demand would increase when the market would transform to kWh as a basis, which is increasingly the case for utility-scale power plants but not for the rooftop segment, which usually absorbs high-efficiency modules.

In summary: When looking at the challenges, it is fair to say that all the above mentioned concerns are teething problems associated with a new technology. There are no real deal breakers for PERC - and there is quite some potential to bring the technology to the next level, as described in the next chapter. But the biggest challenge for any newcomer is the incumbent - in this case standard aluminum BSF. The technology might become so good with some tweaking that PERC may no longer be necessary. Selective emitters is a good example of a technology that lost ground to standard BSF few years back simply because metallization was improved so much that the same efficiency improvements could be reached without adding additional equipment.

6. Taking PERC to the Next Level

WHILE working on overcoming the above mentioned challenges for PERC, the PV industry is also working on methods to take the technology to the next level.

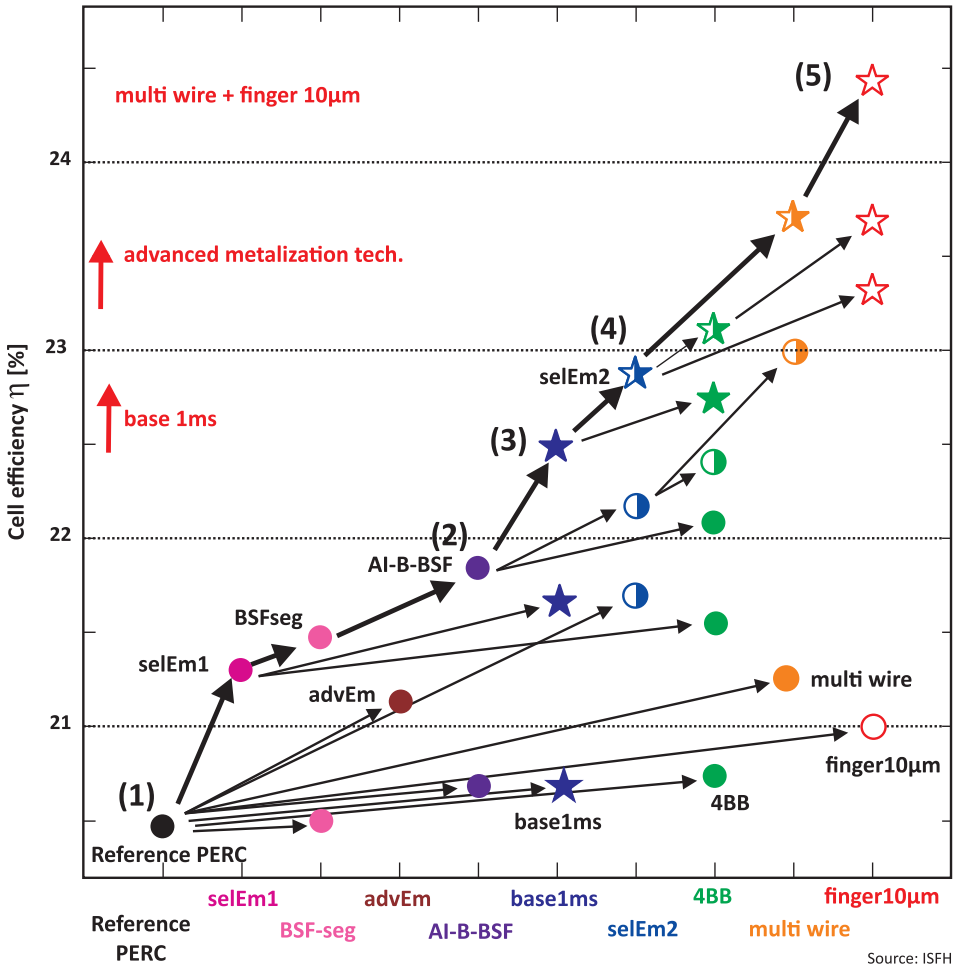
'Standard' improvements: A research group from ISFH has listed key parameters that need to be subject for optimization in the near future in order to increase PERC cell efficiencies:

- Advanced emitter structures such as selective emitters,
- Boron-added Al paste for the rear,
- Wafers with 1 ms lifetime,
- Multi wires instead of busbars
- 10 µm narrow fingers with high aspect ratio.

But except for boron doped aluminum paste, ISFH's above list is a generic recommendation and is also applicable for today's standard solar cells. However, based on these improvements ISFH modeled in 2015 that PERC cells can reach efficiencies beyond 24% (see graph on page 40).

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Impact of Different Improvements on PERC Cell Efficiency



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Research institute ISFH modelled different technology improvements, which can bring PERC cells efficiencies beyond 24% (The star symbols indicate that the efficiencies were reached with improved materials, while the filling of the symbols means that different front metal finger designs are used).

Going bifacial: A real innovation is to adapt the bifacial concept to PERC structures. The approach, also developed by ISFH, is the simplest and most cost effective bifacial structure; a paper was presented at the EU PVSEC in 2015 (*The PERC+ Cell: A 21%-Efficient Industrial Bifacial PERC Solar Cell, Authors: T. Dullweber et al*). The technology of making the solar cell light sensitive on both sides does not add any additional steps to the typical PERC processing. On the rear side, an aluminum grid is applied instead of using aluminum paste for the full area. This method avoids also the usage of silver. A bifaciality ratio of 80 has been attained referring to a front efficiency of 20.8% and 16.7% on the rear side.

Laser Fired Contacts: Fraunhofer ISE has developed a rear metallization concept based on aluminum foils in combination with laser-fired contacts (LFC). At the 29th EU PVSEC in 2014, ISE reported improvements for its Al-foil/IFC-based technology and presented a 21.3% efficient cell with an optimized and simplified process (*Progress in Laser-based Foil Metallization for Industrial PERC Solar*

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Cells. Authors: M. Graf et al.). An alpha lab tool is running at ISE and a production-size beta system will be installed in 2016.

Inherent improvements: PERC also has some potential for optimization. According to Heraeus' Stassen, once PERC matures and overcomes the fundamental hurdles, like LID and improved bulk quality, the focus would again shift to the emitter side. Losses in Voc below the front side contacts will become important again; researchers would work on better passivation below the contacts, smaller contact areas and smaller fingers.

7. PV Experts Views on PERC Technology

THIS chapter summarizes the answers on PERC we received during the interviews for this study between October and December 2015. While the number is too small to show statistical trends, the selected experts we talked to have been deeply involved in solar cell R&D and production equipment sales for so many years, so we decided to present their thinking on PERC in written form.

Overall View on PERC

While all the above announcements speak in favor of PERC, we asked if the technology is really going to take off? The answers were a big Yes! Nearly every PV expert we asked about how important it is to add PERC technology on a scale of 1 to 5 - where 1 is not important at all and 5 is really important - responded positively. The majority ticked 4 or 5 points. NREL's Basore thinks 4 is appropriate, as there will be always a place for aluminum BSF cell technology, where cost is more important than efficiency. But PERC is going to be the winner in any application offering a premium for efficiency. As the majority of field installations are driven by cost, efficiency is only important if it can be increased without adding proportionally to cost. The PERC process requires only few additional equipment tools, but it does not make manufacturing cheaper. Only few markets, with limited space and in the field of rooftop PV, like Japan, have demand for very-high efficiency PV modules. For these reasons, Heraeus' Stassen stayed with a rating of 3 exactly in the middle of the scale when asked if a PV maker has to or doesn't need to add PERC to its process portfolio.

Mono vs. Multi

When segmenting PERC into multi and mono, the opinions vary quite a bit. According to DuPont's Antoniadis, the chances for mono are very high (4 to 5), as the gain is significant enough to compensate all additional manufacturing costs. Regarding multi, no one rated more than 3. Light Induced Degradation (LID) is considered the main obstacle for multi PERC cells. For this reason alone, ISC's Kopecek rated the chances for multi 3 to 4, while Centrotherm's Haase was even more pessimistic (2 to 3) on a scale from 1 to 5.

100% PERC?

Likewise, there are different arguments to the question on how much of the total production capacity would be changed to PERC. The experts believe that new expansion plans are all taking PERC into account; there is nearly no exception. As for the existing capacity a lot depends on the cell makers background. For line upgrades, there needs to be available floor space, which sometimes is not the case, so the additional PERC tools cannot be integrated into a line (although one expert said that those having selective emitter technology can get rid of the wet bench and use the free space for PERC technology equipment). It makes sense to shift to 100% PERC for companies like Solar World, which have spent a lot of R&D time and money on the technology and are mostly selling modules to the residential and commercial rooftop segment. But for newcomers it might take 1 or 2 years to get there, says Semco's Raymond de Munnik. For all these reasons, Levitech recommends cell companies not to go for 100% PERC production, but refrained from providing an opinion on an optimal number.

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Meyer Burger's Erfurt fully believes in PERC technology. He thinks that the initial phase would be a 100% shift of monocrystalline lines, which would happen over the next 5 years. As of now, he considers multi a problem; especially passivating grain boundaries is not easy. In addition to PERC related LID problems, Erfurt believes that multicrystalline as a material itself has to be improved in quality in order to justify the additional investment. But as the technology progresses in all aspects, multi upgrades would take place on a continuous basis. If that does not happen, there would be another possibility - finally it is a small step to change the production line from multi to mono.

Kopecek thinks the industry would move to the kWh sales metric instead of watt peak, which would be beneficial to PERC technology. Thus he recommends a 100% capacity shift to PERC. Basore thinks there will be a 50% capacity shift on the account of playing safe with any new technology. Fraunhofer ISE's Preu believes that 30% of the production would be converted into PERC in the next 2 to 3 years. His estimation is based on the fact that a lot of equipment capacity has to be built, which might slow down the adoption a bit. Since multi is dominating today's market and the association of PERC with this class of material is not yet clear, Haase from Centrotherm estimates that 20 to 30% would be the optimal share for PERC technology for a PV producer.

When looking at today's cell factories, as mentioned above, there are production lines that can not fit in two more pieces of equipment, and for some lines it is not worth to consider any upgrade as the lines are too old. Thus Trina Solar's Chief Scientist Pierre Verlinden says that PERC implementation would take the path of capacity additions rather than line upgrades.

Estimates on PERC Capacity Additions in 2015 / 16

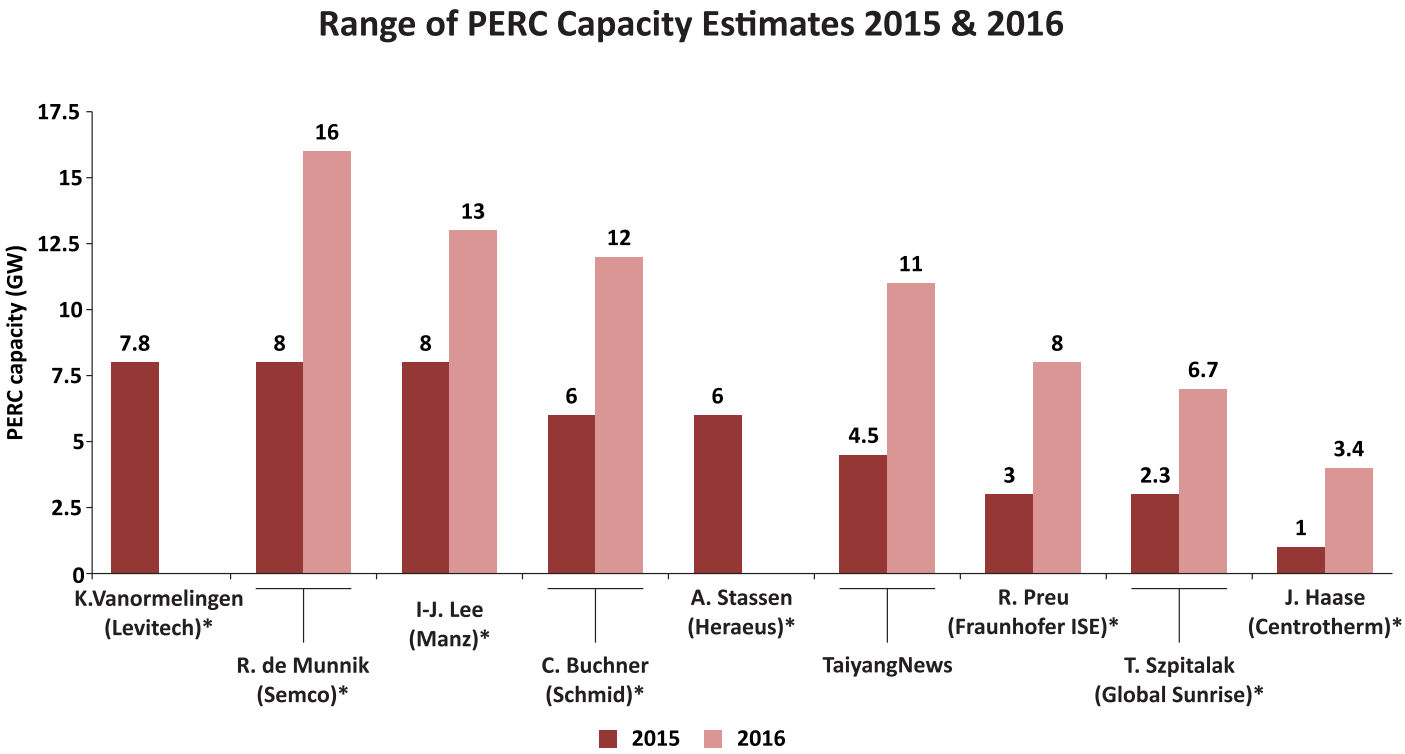
Taking all these projections into account some experts gave estimations for PERC production capacity additions in the short term - 2015 and 2016. Christian Buchner, CEO at Schmid Technology, says that about 6 GW was installed in 2015 and about the same will be added this year. According to SoLayTec, 7 to 8 GW of capacity was sold in 2015. Agreeing with this estimate, Semco's de Munnik forecasts 8 GW more PERC tools will be installed in 2016. However, ISE's Head Production Technology Ralf Preu says that only lines with capacities of 2.5 to 3 GW were installed in 2015, but the capacity would be 8 GW by mid of 2016. That's because lot of equipment has been ordered within the last 2 quarters of 2015 and was ready for shipping only towards the end of the year. Ted Szpitalak, Chief Operating Officer of Sunrise Global, also provides a similar estimate - 2 to 3 GW by end of 2015 and 6 to 7 GW in 2016. According to Arno Stassen, Head of Global Business Development at Heraeus, the installed PERC manufacturing capacity was about 6 GW end of 2015, which is expected to be doubled over the next 2 years. Manz estimates are based on orders for production equipment, which it believes was 8 GW by the end of 2015 and about 5 GW in 2016. Josef Haase, Centrotherm's SVP Technology & Sales, provided the most conservative estimates -1 GW in 2015 and 3 to 4 GW in 2016, but emphasized that these numbers refer to operating production systems. Because, though several systems have been installed, not all of them have been running in full production, he said (see graph on page 43).

8. Beyond PERC

WHAT are the other silicon cell technologies beyond PERC that are ready for commercialization? There is no easy and simple answer - so we've just summarized some comments on these challengers from industry experts we've talked to:

P or N-Type: It starts with the questions if p-type will continue to dominate or if n-type will take over. For Centrotherm's Haase, n-type lost its charm, as the LID effect is under control for p-type monocrystalline cells. Semco's de Munnik, on the other hand, thinks that the next technology upgrade would be n-type bifacial structures. Because, they are closest to p-type manufacturing. The wafer price

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* Numbers are not official company estimates, but personal views of employees interviewed

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Difference of opinion: Nearly every industry expert we talked to agrees on the bright prospects for PERC, but estimates for capacity additions differ a lot.

is still challenging, but cell process pricing is getting better and better and contacting is becoming mature. One specific advantage of n-type bifacial cells is that the rear efficiency for these cells is high. Taiwanese cell maker NSP has demonstrated a bifaciality exceeding 90%.

PERT: Equipment maker Schmid Group is strongly betting on Passivated Emitter, Rear Totally Diffused (PERT) architecture adapted to both n-type and p-type in the near term. Unlike standard cells and PERC cells, which both use an aluminum-alloy BSF (full area for standard, local for PERC), PERT cells have a diffused rear surface. That means, with n-PERT the emitter of n-type based wafer is formed with boron diffusion and BSF is realized with phosphorus doping, while it is just reverse for p-PERT. Schmid is already promoting p-PERT as an alternative to PERC, especially for multicrystalline, as the technology does not have any limitation such as LID. ISFH's Dullweber believes that n-PERT cell technology will become dominant primarily because of its bifacial features. Belgium-based research center IMEC presented a 22.5% efficient industrial size-PERT cell in mid-2015; in early 2016, it extended a research project with SunPower's parent company Total on n-PERT technology. There are also already a few commercial products on the market. In December, Chinese cell and module manufacturer HT-SAAE announced that the power rating for its n-PERT 60-cell (156x156 mm) module was increased from 285 W in Feb. 2015 to 300 W equal to around 18.4% module efficiency in Oct. 2015.

PERL: There also exists a combination of PERC and PERT that is called PERL, an abbreviation for Passivated Emitter Rear Locally-diffused solar cell. As with PERC, the front surface as well as the rear surface of the cell are passivated, but the rear is locally diffused only at the metal contacts. The

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technology, also developed by UNSW's Green, held the world record efficiency for silicon solar cells for many years. But commercial production is still in the early stages: Korea's Hyundai Heavy Industries (HHI) announced in October 2015 to upgrade 200 MW cell capacity to PERL technology by early 2016, which it has been developing since 2010. The record efficiency for HHI's PERL cell is 21.4%.

Tunneling Oxide: Fraunhofer ISE's Tunnel Oxide Passivated Contact (TOPCon) cell is other technology that has recently gained some attention. In September 2015, at the EU PVSEC, ISE announced a cell with a conversion efficiency of 25.1%, taking over the world record for silicon solar cells *(The Irresistible Charm of a Simple Current Flow Pattern - Approaching 25 % with a Solar Cell Featuring a Full-Area Back Contac; Authors: S. Glunz et al.*). The cell features selective passivated contacts made of tunnel oxide on the rear side. It is based on the principle of a very thin passivation layer of about 2 to 3 nm, which allows the charge carrier to tunnel through it. This layer is topped with a highly doped silicon film. US start-ups Tetrasun (now owned by First Solar) and Silevo (now owned by SolarCity) have developed cell technologies based on the tunneling oxide approach.

IBC: Not only does Schmid believe that n-type will become mainstream very soon, it thinks that within 2 years Interdigitated Back Contact (IBC) will gain increased interest. This technology benefits from eliminating shading losses completely as the contacts of both polarities are entirely placed on the rear side. The front surface receives a blanket doping profile, while the rear of the cell has alternate zones of p+, and n+ regions, which are also realized with active doping. The top efficiency for IBC cells is 24.2%. The tradeoff is that production of IBC technology is rather complex, says Centrotherm's Haase - and indeed, so far SunPower is the only company that has been able to master large-scale production of IBC technology, though at rather high cost-per-watt. Still, Schmid's Buchner considers IBC technology the ultimate level.

HJT: Heterojunction silicon-based solar cells are made by sandwiching the high quality silicon wafer between doped and intrinsic amorphous silicon thin film deposited layers. So far, only Japanese company Panasonic is offering large-scale commercial PV products based on HJT architecture. In October, it announced a 22.5% efficient prototype (270 W, 72 cells) using mass-production technology. Panasonic also holds the world record for HJT cells - in 2014 it reached 25.6%. Meyer Burger is offering a turnkey solution for HJT cells.

When looking at all these technologies a good **analysis** was provided by Pierre Verlinden, Chief Scientist at the world's larges module manufacturer Trina. Verlinden sees n-PERT to be the next step after PERC - it has most of the advantages of HJT efficiency, but with a better compatibility with existing production lines. IBC will stay a premium technology - with higher efficiency, but also higher cost. It will be reserved for premium applications, where efficiency and aesthetics play a vital role. Verlinden considers HJT somewhere between PERC and IBC, both in terms of efficiency and cost. But he emphasizes that HJT is not very compatible with standard production lines, which poses a challenge regarding capex. However, ISFH's Dullweber thinks it is likely that several technologies exist in parallel for the next couple of years.

9. Conclusion

ALL solar cell manufacturers that are evaluating capacity expansion in the current investment cycle have to decide if they stick to traditional technology or opt for advanced solutions. The simplest and most attractive silicon cell technology upgrade is called PERC, which stands for Passivated Emitter Rear Contact. It only needs a pair of additional equipment to upgrade a standard line, which can result in efficiency improvements of up to 1%. As this report shows there are still a number of challenges that need to be overcome, especially for multicrystalline cells. But when looking at these challenges, it is

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fair to say that all concerns are teething problems associated with a new technology. There are no real deal breakers for PERC - and there is quite some potential to bring the technology to the next level. Not only is the production equipment available, many companies have started mass production of PERC cells, and capacities are being added quickly. We estimate that 4.9 GW of PERC capacity was installed in 2015, resulting in 3 GW of PERC cell production. This year, the cumulative production capacity could reach 11.8 GW, and 8.1 GW PERC products could hit the market. As commercialization of the technology is taking speed, record efficiencies are quickly being broken for PERC, reaching 22.13% for mono and 21.25% for multi (status mid Feb. 2016). It is true that there are several other promising technologies being developed, but moving to PERC is rather simple - cell makers only need to add 2 machines (ALD deposition and laser systems). One CEO of a leading Chinese cell manufacturer told us in case PERC would be able to reach 23%, he doesn't see a bright future for hetero-junction technology. Research institute ISFH has modeled how PERC can attain 24% efficiency with rather simple improvements. That's why the researchers are convinced that, "The predicted efficiencies lead us to the conclusion that PERC cells will dominate the market and define the moving target for some time to come." This is basically inline with the forecast of the 2016 released 7th edition of the International Roadmap of Photovoltaic (ITRPV) roadmap, which expects PERC technology to gain about 7% market share in 2015 (and is down from 10% in the previous version); our research suggests that it still was rather 5%. But the new capacity expansion cycle started later than expected. While we see about 12% PERC share in 2016, ITRPV forecasts that PERC production increases to 14.5% in 2016. Unlike in the past, ITRPV now combines PERC together with PERT and PERL for its long-term forecasts, which are nevertheless lower than its previous PERC estimates. Only time will tell. But if other companies than just QCells and REC will have LID under control for multi and move into that sphere, there is lot of potential to gain for the rather simple and low-cost PERC technology.

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