Riding the workhorse of the industry: PERC

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Abstract

Improving PERC cells requires rather different strategies than standard cells have required, demanding concrete improvements in materials, manufacturing procedures and fabrication tools. Highlights of this paper include:

Highlights

- In recent years, PERC cell efficiencies have increased by about 0.4%_{abs} per year in mass production. This paper discusses how the industry's median efficiency can be increased to 24% within about seven years while fabrication cost may drop to about half.
- A simulated roadmap shows that, presently, efficiency is either limited by a homogeneous emitter, or in case of a selective emitter by wafer lifetime. The next improvements are cleaner fabrication, Ga doping of wafers to reach 2 ms lifetime, better emitter profiles and emitter passivation, finer metallization, and improved hydrogenation.
- 24% efficiency will not be reached by solely optimising existing technology, but by steadily improving existing technologies further, which requires continuous R&D efforts and the further development of some specific manufacturing tools.

Figure 1. Efficiency of sold monocrystalline PERC modules, calculated from the module's power and area listed on manufacturers' websites. The date is the latest update of each web page, which may lag behind fabrication by up to one year. Adapted from [1]. The present PERC cell efficiencies of large Chinese manufacturers are typically up to 21.4% with homogeneous emitters, and from 21.5% to 22.2% for selective emitters. The selective emitters are mostly fabricated with laser doping of the n⁺⁺ part; some use selective etch-back, which offers greater flexibility. The highest efficiencies are obtained with both wafers near the seed end of the ingot and clean processing, so the bulk lifetime in the



finished cells is high. Manufacturers tend to buy wafers that are thinner (mostly 170 μ m), larger (mostly M2 with 156.75 mm side length and 210 mm diameter), and with lower resistivity, typically 0.5-1.5 Ω cm. We have monitored [1] the evolution of PERC module efficiency over recent years by consulting the main manufacturer's websites, taking their median module power divided by module area, see Fig. 1.

The date in the graph is the latest update of each web page, which may lag behind fabrication by up to one year. The graph does not aim at completeness but to reveal the trend. We fit the efficiency trend over the years with the Goetzberger function [2] (dashed line):

$$\eta(t) = \eta_{\text{limit}} \left[1 - \exp\left(\frac{t_0 - t}{c}\right) \right],$$

because it considers that efficiency saturates towards a practical efficiency limit η_{limit} . In our data fitting, the development speed c turns out to be 21 years, meaning that the curve is still rather close to linear (the starting time t_o at zero efficiency has no practical meaning). Presently, PERC module efficiency increases by about 0.4%_{abs} per year, and this trend can continue for the coming years under conditions discussed in this paper. Part of this steady progress in China is fostered by a high staff turnover, where skills and knowledge is exchanged between manufacturers. Another part is an ongoing optimization of PV tools and screen-printing pastes, which have played an important role.

Roadmap for PERC cell efficiency improvements

Two detailed roadmaps for PERC cell efficiency improvements were published in [3] and [4,5]. The latter was obtained with detailed Sentaurus device modelling, and an updated version is depicted in Fig. 2.

The roadmap started in 2015 with a bulk SRH lifetime of 350 µs and a rather poor emitter. Meanwhile, most manufacturers have at least an advanced homogeneous emitter (advEm on the x-axis of Fig. 2) or a selective emitter (selEm1) with a sheet resistivity near $\rho_{\rm sh} \approx$ 160 $\Omega/$ sq. Additionally, they shape their local BSF with segments instead of lines (BSFseg), they add boron to their Al-paste (Al-B-BSF), and have five



Figure 2. Roadmap of monocrystalline PERC cells, simulated with Sentaurus assuming present materials and technology being steadily developed further (no break-through technologies). Black: task fulfilled since 2015 by most manufacturers. Stars: wafer materials with 2ms lifetime; filling of symbols: various front metal finger designs with 91 fingers/60 µm wide (filled), 155/30 (half-filled), 155/21 (empty). Updated from [4,5].

busbars (5BB), some already multi-busbars. Their present-day cell efficiencies are predicted by this study very precisely, considering that such a study cannot take manufacturers' individual details into account. This gives trust that the predictions for further cell efficiency improvements are reliable.

For improving PERC cell efficiency further, this graph shows two important features: firstly, with already existing technology continuously improved further, about 24% PERC cell efficiency can be reached in mass production (no passivated contacts or other emerging technologies like hetero-emitters have been considered). Secondly, each technology needs to be improved at its right time, as becomes obvious for example with the last improvement in the graph: the rear passivation (Srear). The arrow from the starting reference pointing to this improved rear passivation is practically horizontal, while the arrows above 23% efficiency increase steeply. This has the following reason: at the reference point, recombination at the rear passivated surface is small compared to recombination in the emitter and the base region. Hence, reducing recombination at the rear does not lead to a noticeable reduction of recombination. However, once the emitter and base regions are improved so the cell reaches 23%,

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The innovative solution for PERC cell manufacturing control

- Quality control of: » AR-coating on the **front side** of mc-Si and c-Si cells
- » passivation layers on the **back side** of mc-Si and c-Si cells
- Long-term stability monitoring of deposition processes
- Easy recipe based push button operation
- Software interface for R&D
- Touch screen operation & interface for data transfer

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reducing recombination at the rear has its impact. Hence, reducing the dominant recombination losses increases cell efficiency far more than reducing smaller recombination losses. Thus, knowing the dominating recombination losses [6] indicates where to improve the cell next.

This implies that the rear Al₂O₃-passivated surface is currently too good [5] and its further improvement would hardly influence efficiency. Some manufacturers therefore currently use an oxynitride [7]. However, with improving other losses in the cell in coming years, finally rear passivation will become important and oxynitrides are expected to become efficiency limiting. Hence, investing in Al₂O₃ passivation is not wrong, but it is an investment mainly for the coming years. The roadmap in Fig. 2 may guide manufacturers to buy tools to avoid a 'legacy lag' in the near future.

The fact stated at the beginning of this article - that, presently, changing from a homogeneous to a selective emitter improves efficiency considerably - shows that a homogeneous emitter is currently limiting efficiency. This is so although inactive phosphorus [8,9] has been largely reduced, contributing greatly to efficiency improvements also of standard cells in recent years. With a selective emitter, usually the wafer lifetime causes the dominant losses. There is still some uncertainty about how the lifetime in p-type wafers may improve. The stars in Fig. 2 can only be reached with 2 milliseconds (ms) final bulk lifetime at MPP, demonstrating how important high lifetimes will be. Two ms has been reached with boron doping in the laboratory at ISFH, Germany, since 2016 for $2 \Omega m$ Cz material after re-generation [10]. It was also nearly achieved with Ga-doped wafers 30 years ago [11] and with an industrial Cz puller 20 years ago [12]. Although iron reduces lifetime more in Ga-doped than in B-doped material [13], it looks like that 2 ms final lifetimes with Ga-doping will soon be on the market on a large scale, because the Ga doping patent from Shin-Etsu is going to expire soon. Ga does not cause light-induced degradation as long as there are no large amounts of Cu in the material [14]. Hence, the regeneration tools will soon not be necessary anymore (but they may be useful one day again for hydrogenation of passivated contacts).

Important is not only the initial wafer lifetime; the final bulk lifetime after fabrication determines cell efficiency, and it may be limited by the degree of cleanliness in many production facilities. This is particularly the case in lines that were upgraded from old standard to PERC manufacturing or in lines where mono and multi materials are used alternatingly, despite standard cleaning procedures between material changes.

For cleaner fabrication, factories may adopt changes including the following:

 Purer quartz tubes. Purer ones cost about fivefold than the standard fittings, but the cheap



Figure 3. Evolution of front metal fingers: their width (causing shading) and crosssectional area (causing resistive losses). Literature values (symbols) with the indicated printing techniques, arrows indicate trends. The width (and area) of other printing techniques are slightly adjusted to the optical factor (and resistivity) of screen-printed fingers for direct comparison. Adapted from [21].

ones tend to cause a clearly noticeable degree of contamination.

- Clean air. An air class 1000 throughout the manufacturing line won't be sufficient for higher efficiencies.
- Avoiding impurity drag into the line from sawdamage/texturing. If the materials used in the machines for saw-damage etch become porous or brittle, they store and release old impurities into the new chemical bath. Also, it is important that these chemicals are renewed in a way that no old liquids stay in the system.
- Carefully monitored deionized water having high resistivity is also important.
- Impurities may travel from saw-damage down to the firing furnace via conveyor belts, roller bearings, and handling systems (originating also from lubricants and mechanical wear). Contactless wafer handling may seem costly at the moment, but if the PV industry adapts it on a large scale, it should be affordable and will enable higher efficiencies.
- Automation may help. But before that, simple procedures may help sooner, like removing metallic door handles as well as metal lids on the floor, not allowing fork lifts to enter the premises, protecting the operators' mobile phones, etc.

If cell efficiencies well above 22% should be reached, the cleanliness procedures in production facilities may look rather different from how they look now, regardless of whether n-type or p-type material will be used.

Apart from cleaner production, an improvement of hydrogenation may increase the final lifetime as well. Presently, hydrogenation takes place during the firing step and during re-generation, where the hydrogen stored in the SiN_x layers readily diffuses into the cell. The transport of hydrogen at medium temperatures is being better understood thanks to progress in research and models [15]. Also, it is not completely clarified yet whether, sometimes, too much hydrogen is left in the final device, creating more defects than passivating. More research into hydrogenation may help to improve the final bulk lifetime in PERC cells considerably.

Presently, some recombination loss may occur at the rear metal contacts if the BSF depth is smaller than about 4 µm at locations sideways very close to the rear surface. Recombination in the Al-Bdoped region is dominated by the Al-O complex [16] so a BSF depth of about 4 µm is optimum [17]. If the BSF is sub-optimal, recombination at the rear contacts can easily become a major contribution to efficiency variations, and it is important to distinguish this from failures or contamination in rear surface polishing or passivation.

In case manufacturers succeed in fabricating a good BSF, further improvements in the emitter may help next. There are various ways to do this in parallel. One possibility is improving the alignment of screen-printing so the n⁺⁺ region can be narrower. The selective emitters fabricated by laser-doping may be improved by reducing the phosphorus dopant density in both $n^{\text{++}}$ and n⁺ regions by further process tuning. Certainly, a better front passivation beyond the usual SiN, is beneficial (Sfront in Fig. 2). This creates possibilities to further reduce the dopant density at the surface by etching the lased-doped, selective emitter homogeneously back (selEm2). This reduces mainly Auger losses in the n⁺⁺ region and, if the front surface passivation is good enough, also the recombination losses in the n+ region. Provided that a good front surface passivation is achieved, a 0.4 µm deep n+ emitter with a phosphorus concentration near 1×10¹⁹ cm⁻³ at the surface would be optimum, because its sheet resistivity stays below 350 Ω /sq and its J_{o} reaches 10 fA/cm² [18]. This is expected to be achievable with POCl3 diffusion and etch-back.

Of course, a considerably larger sheet resistivity ho_{sh} may increase the resistive losses. Increasing the number of metal fingers only helps reducing these resistive losses if the fingers are sufficiently thin so they don't cause too much shading (finger30um). There are two effects helpful in optimization: (i) in the module, the shading losses due to the front metal fingers are reduced compared to air due to back-reflection at the front glass, quantified by a reduction of the 'optical shading factor' from 0.69 in air [19] to 0.42 in the module [19,20]. (ii) At low $\rho_{\rm cb}$ the electrons flow from the base region straight up to the emitter and then flow sideways along the emitter to the contacts; but with increasing $\rho_{sb'}$ an increasing proportion of electrons flows along a curved path in the base. The front finger

distance and $\rho_{\rm sh}$ of the emitter should therefore be optimized taking all these influence factors into account, not just a few.

In this context, the question arises which further improvements in metallization are necessary and most beneficial. Not now, but once the emitter is improved and has a lower n⁺⁺ doping, introducing a narrower front contact opening of about 10 µm (Cont10um) instead of the whole finger width will improve cell efficiency. This was already achieved in the Pluto cell (at that time with plating). Fig. 3 shows the evolution of the front finger width (determining shading) and the finger's crosssectional area (determining series resistance) over time [21], collected from literature.

In order to plot Ag or Cu plating in the same graph, its area was adjusted by $\rho_{\text{\tiny SP}}/\rho_{\text{\tiny Ag}}$ and its width by the reduced shading factor to 0.32 (hence, by 0.42/0.32). The graph shows that it has been too early to adopt plating (dashed lines), but with reaching multi-wire/multi-busbar designs, plating can become a more serious competitor to screen printing, although screen printing is poised to arrive at 30 µm finger width with knotless printing rather soon, enabling great flexibility in emitter optimization. If silver price rises considerably, silver consumption needs to be reduced from presently below 100 mg/cell with five busbars and below about 50 mg/cell with multi-busbars or multiwires. Twenty mg are doable [22]. Only if this is still too much silver, Cu fingers may become the solution. To avoid Cu diffusion into Si over 30 years of module lifetime, an initial 200 nm thick Ni or NiSi layer is necessary [23], and to avoid vellowing of the EVA, a very thin layer of Ag on top of the Cu helps. All in all, the desired finger width and cross-sectional area are near the bottom of the left corner in Fig. 3. For example, the 25% efficient PERL cells at UNSW in the 1990s had $\rho_{\rm ch} \approx 200 \,\Omega/$ sq, a finger distance of 0.8 mm and an optimum finger width of 20 μ m in 2 × 2 cm² cells [24]. Also calculations and laboratory experiments show [22] that for multi-wire/multi-busbar designs, the metal finger width does not need to go below 20 µm. The roadmap for the front fingers does neither ask for high aspect ratios, offered by some alternative printing methods, nor for geometries narrower than 20 μ m, and most benefits are already obtained with 30-25 µm.

For module power, improvements in cell efficiency have the strongest impact because most of the module area is covered by the cells, not by the white spaces. Apart from efficiency improvements, some other measures at the cell level may additionally foster improvements in the module. For example, using officially calibrated cells for precise tuning of the IV tester, and carefully adjusting the operating parameters of the IV tester may help. It can easily happen that cell efficiency is measured about 0.5% abs too high. An overestimated cell efficiency implies an underestimated cell-to-module (C2M) ratio, making it difficult to evaluate where to improve the module. And it makes also OEM fabrication more difficult, which has become a considerable factor in the PV industry. Establishing a Chinese ISO-17025 accredited IV Test laboratory would certainly improve the current situation in the Chinese PV industry. Even the gratifying row of latest world record efficiencies of industrial-type PERC cells were not officially calibrated and, hence, these efficiency levels should be taken with some caution so long as these manufacturers do not compare themselves with certified measurements. The efficiencies of these champion cells fit into the roadmap of Fig. 2, though.

Not all improvements on the cell level can be transported to the module level. An example occurred when the industry moved to double AR-coatings at the front to prevent potentialinduced degradation (PID): the higher refractive index of EVA made the double ARC ineffective. We will see a present-day example of black silicon texturing below: it may improve the cells in air, but not as much in the module. Doing a detailed optical analysis [25,26] helps to quantify the benefit of the optical improvements in the cell for the module, and it avoids possible mutual blaming between the cell and module manufacturing departments for delays.

Timeframe for improvements and production cost

The expected timeframe of efficiency improvement can be estimated by combining Fig. 1 with Fig. 2: it may take about seven years to reach 24% PERC cell efficiency in the industry's median. This is assuming that neither major interruptions nor breakthroughs will occur. Fig. 4 shows the fabrication cost decay [27] (not only the sales price). An extrapolation [1] suggests that, by then, module cost may drop down to about half of today's cost, which is at the present overcapacity cycle near RMB 2.5/W.

Main contributions to cost reduction have come from cheaper PV tool manufacturing in China, standardization all along the value chain, and a fierce fight for gigawatts. Recently, a very swift change from slurry-saw wafers to diamond-sawn wafers has reduced CAPEX for poly silicon (before, it caused over 30% of CAPEX required for the value chain up to the module). Now, only four grams of poly-Si are required per watt. A reduction in CAPEX is very beneficial for the further scaling up of the Si PV industry. If solar cells should contribute significantly to reducing CO, the global cumulative installed capacity needs to go beyond 10 TW [28], compared to about 0.4 TW installed now, and hence the production capacity needs to grow about 10-fold. This implies that



silver consumption per cell eventually needs to be reduced [29].

Reducing wafer thickness can further reduce CAPEX. This may occur rather slowly from the present 180-170 µm to, say, 140 µm, not because of yield problems but because J_{sc} gets smaller. The J_{sc} losses depend on texturing and light trapping. We should keep in mind that, with standard texturing and AR coating, cells can look already black in the module (although many manufacturers adjust the AR coating thickness such that the cells look blue). Overall, the main reflection loss comes from light escape in the infrared [24], followed by absorption losses in the module glass and by EVA. Different texturing, often coined as black silicon, can therefore increase a 60-cells module's power only by maximally 1 W by reduced front surface reflection alone. However, improved texturing may distribute the sun rays, entering the wafer, more evenly so more light gets absorbed and less escapes in the infrared, by an amount that depends strongly on the reflectance at the rear cell surface: about 3 W may be realistic, 4 W is absolute maximum, as ray tracing simulations show [30] (if higher gains are observed, they come from an accompanying reduction of emitter *J*_o and an increase in collection efficiency due to changes in the front surface topology).

A further important cost reduction will continue to come from higher throughput. Fig. 5 shows how throughput has increased over recent years. The data of texturing and PECVD tools are from S.C New Energy Technology Corp. having 50-60% market share in China; the other tools are averages from various manufacturers. Increasing throughput is very effective because it reduces many different cost aspects.

Also, the margin may continue to shrink, and may continue to force either large manufacturers to become larger, or smaller manufacturers to find their own ways of keeping their cost and overhead very low. By how much a further automation of manufacturing lines will reduce cost in China is too early to judge.

In maturing industries other than PV, increasing process control tends to be a cost saver when margins get small and competition more subtle, and this may also be the case in PV. In many factories, underperformance of cells discovered by the IV tester cannot be traced back directly to the tools because it is not monitored at what time the cells went through which tools in batch processing; on the way, cells may be on differently sized boats and carriers and get spontaneously diverted when a piece of equipment is down. In PERC fabrication, quite some time may pass from saw-damage etching to firing and re-generation. Basically, this is a lack of information that hampers a concrete feedback. Information can be seen as entropy, and the state of the fabrication system becomes better defined by either maximising or reducing



Figure 4. Crystalline silicon module cost [26] and future estimate [1], compared to module price.

entropy. Maximising entropy means shuffling a large amount of wafers before feeding them to the lines so all the tools get the same statistical mix of wafers - making any underperforming tool stand out after some time. Reducing entropy means either improving traceability of the wafers or closer monitoring of the tools, or both. It is not necessary to trace every single wafer, but helpful can be for example RFID coding of boats and carriages, designing smart handling systems, or real-time monitoring of the tools that cause most of the efficiency variation. Statistical methods help to pin down these tools [31,32,33], and if statistics is combined with device physics, efficiency can be improved even better. Because bulk lifetime tends to be limited by cleanliness, tracing bulk lifetime though the production process is advantageous. Etching back some cell precursors from various stages of fabrication and (re)passivating them is an option. As Al₂O₂ passivation is done at elevated temperature, superacid passivation [34] can be done at room temperature, so the lifetime is not influenced by an additional thermal budget. A further possibility for enhanced process control is to go beyond monitoring the IV parameters alone, which is mostly just efficiency. Some brands of IV testers may measure more cell parameters including the pseudo fill factor (pFF), a reliable R., wafer doping concentration, the sum of back and front J_{α} and bulk lifetime [35]. These parameters are very helpful in tracking down short-term or long-term problems. Last but not least, the cell's capacitance increases strongly with increasing $\mathrm{V}_{_{\mathrm{MDD}}}$



Figure 5. Historical development of throughput of tools made, as well as the typical CAPEX required for 1 GW of PERC cell manufacturing capacity built in China. Adapted from [1].

[36], making special procedures necessary in most IV testers to avoid hysteresis. If such IV testers are not updated, IV parameters may become unreliable (e.g. overrating efficiency).

Process control is expected not only to narrow down the cell efficiency distribution, but also to increase efficiency. Over the years, standard, full-area BSF cells could be optimized partly with 'trial and error' because the variation of process parameters has impacted cell efficiency in a quite straight-forward manner. And the high numbers of cells produced made small increments statistically significant. PERC cells, however, have considerably more process parameters, and parameter alterations interact in a complex manner with other parameters. This complexity restricts optimization by 'trial and error' to the point that other approaches need be developed to optimize PERC cells swiftly, like the statistical methods mentioned above.

It is important to realize that optimization alone is not sufficient to arrive at 24% PERC cell efficiency. The simulations of the roadmap assume that existing technology is steadily being improved, not just optimized, hence R&D is important for further technological improvements of tools, materials and processes. Questions to answer include:

"In maturing industries other than PV, increasing process control tends to be a cost saver, and this may also be the case in PV"

- What needs to be changed in cell manufacturing so 2 ms bulk lifetime can be achieved in the final cell on large scale?
- Which is the next tool? Does improved front surface passivation require new or adjusted tools or only new materials and processes with existing tools?
- Should tools and pastes be developed already now to enable smaller contact openings than metal finger width? These tools need to be ready to be bought and sold on a large scale only once the emitter is so good that the front contact contributes significantly to the overall recombination losses.
- Can hydrogenation be significantly improved and, if so, how?
- Silver contributes considerably to the manufacturing cost and will increasingly do so. What will be the tools and material requirements for reducing silver consumption below 40 mg/cell?
- While seed ends of ingots reach 2 ms lifetime, how can the lifetime in the rest of the ingot be improved?

Table 1 lists the eight main processing steps of PERC cells and their supposed origins. It is striking how many of these processing steps originated from universities and other public institutions. However, PV tool manufacturers were necessary for implementation, sometimes in close collaboration with these institutions and aided by government grants. When considering the PERC road map, we should ask questions like: where are new and improved process steps being invented today? Where is collaboration between inventors and PV tool manufacturers happening? Is there enough government funding for this? Which tool manufacturers actively develop equipment for implementing such new process steps? Besides having the 'Top Runner' programme in China fostering high-efficiency cells, it may be beneficial to also have a 'Top Tools' programme for actively fostering new types of tools.

N-type or p-type?

Most PV tool manufacturers do a great job at optimizing tools, as for example seen in the throughput in Fig. 5. However, because PERC is still in a rather early stage of manufacturing, most PV tool manufacturers do not yet seem to know concretely how to improve PERC cell efficiency beyond optimization and do not seem to prepare new tools particularly for this. Most Chinese PV tool manufacturers undertake hardly any R&D activities beyond optimising existing tools, with some notable exceptions like Laplace, Leadmicro, Maxwell, DR Laser (and surely some others we missed out). Instead, some tool manufacturers hope that switching to n-type wafers will deliver the necessary further efficiency improvement and will foster the sales of new equipment like LPCVD, new screen-printing pastes, etc.

Some large cell manufacturers invest more R&D in n-type than in p-type cell development, although they mainly produce p-type cells, and do this although their calculations mostly indicate that n-type is rather unlikely to compete with p-type in the near term. This may be partly caused by insecurity about how to improve PERC cells beyond 22% efficiency, and partly by a "we do so because the others do so" effect (which is important for minimizing risk of missing new trends). Both these aspects may become a self-fulfilling prophecy: because manufacturers focus more on n-type R&D, PERC development may get partly neglected over time and indeed may not go far above 22% - and because many manufacturers build n-type lines the same time, prices for manufacturing of n-type cells may significantly drop.

Let's play the devil's advocate. Here are some aspects for staying with p-type:

- Manufacturing both a local, deep Al-BSF and rear local metal contacts in one firing step is hard to beat. We are very lucky that Al is both a dopant and reduces the melting point of silicon, while Ag pastes work excellently on n-type emitters (in contrast, pastes don't work as well on p-type emitters in n-type cells).
- The p-type community has PERC as a clear and single target and concentrates its efforts and supply chain standardization on that, while the roadmap for n-type seems unclear so the n-type community disperses its efforts and power among n-PERT, n-type passivated contacts, HIT, and IBC.
- All well-developed cell types like PERC, PERT, IBC, and HIT, be it on p-type or n-type, move towards a similar practical efficiency limit in mass fabrication, which is between 25% and 26% [37]. Hence, differences in manufacturing cost will become even more important than they are now, favouring PERC.
- Research in lifetime-limiting defects for p-type is well established and well on the way, while many n-type advocates think that n-type won't be affected by defects. However, both material types contain oxygen and other impurities.
 While oxygen decreases FF in PERC cells, it increases FF in n-type cells by reducing Voc, an often overseen effect [38].
- Phosphorus diffusion is the cheapest way to getter the material efficiently, boron diffusion does not getter as much [39].
- The phosphorus-rich layer (PSG) has a more negative formation enthalpy than the boron-rich layer (BSG), hence PSG collects and removes significantly more impurities from the process than does BSG. Considering the issues with clean cell production, discussed above, PERC efficiency will be easier to maintain on high levels than n-type cells over the long term.

Process step	Origin and year
Texturing	General Electric Ltd 1969
P diffusion	US Army 1962
Rear side polish	RHENA, imec 2008
Selective emitter	Laser doping via PSG: University of Stuttgart, 2009; Etch-back: University of Konstanz, 2008
Passivation by SiN _x ; by Al ₂ O ₃	University of Erlangen 1989, ISFH 1995; imec, TU Eindhoven 2006
Rear laser opening	ISE Freiburg 2000
Screen printing	Spectrolab Inc. 1973
Firing	BSF: ARCO Solar 1988; Firing through: Mobil/Schott Solar 1997 and imec, University of Konstanz 2000

Table 1. The eight main processing steps of PERC production and their supposed origins (not aimed at completeness, but to show the deep involvement of universities and other public institutions).



Figure 6. Simulated monocrystalline PERC cell efficiency with increasing homogeneous concentration of a single contaminant as indicated. This suggests that p-type (solid lines) is less sensitive to these contaminants than an equivalent cell structure on n-type (dashed lines) if Fe is under control. Adapted from [37].

- The Sentaurus simulations [40] in Fig. 6 suggest that n-type cells are more sensitive to metal impurities than p-type cells – once Fe contamination is under control.
- For development beyond PERC, cells on p-type wafers offer better opportunities for passivated contacts than on n-type wafers. This is so because a hole-conducting contact is more difficult to achieve than an electron-conducting contact (due to differences in tunnelling mass and required work functions). Hence, electron-conducting contacts can be used locally at the front (making a conducting oxide for lateral

"The PERC cell may be developed into a PERC+ cell by incorporating features such as passivated contacts, hetero-emitters and hetero-BSFs"

conduction obsolete), and the hole-contact can be spread across the entire rear surface, allowing its contact resistivity to be as high as $30 \text{ m}\Omega\text{cm}^2$ [41] and its J_0 as high as 20 fA/cm².

 Tools for n-type cells are difficult to maintain (for example dust in LPCVD, furnace tubes for boron diffusion, etc.), and there is considerable absorption of light in both a-Si of HIC concepts and poly-Si front passivated contacts. And now comes the devil's advocate with

aspects favouring a change to n-type:

- Many cells made of n-type wafers have always had higher efficiency than on p-type, this is a well-established fact, and there are no signs why they should not continue to do so.
- The defect engineering of p-type material should not be trusted; the stars in Fig. 2 show what will happen to PERC cells if final lifetime cannot reach 2 ms in the whole p-type ingot. Lifetime in Cz n-type mono wafers can easily achieve milliseconds, while most of p-type mono wafers are a few 100 µs.
- There is less light-induced degradation in n-type than in p-type, even with the current deactivation procedures for p-type.
- Boron diffusions reach lower J_{\circ} values than phosphorus diffusions and are not significantly more expensive in 24/7 fabrication if BBr₃ is avoided.
- PERT designs have significantly better bifaciality than PERC. Improving bifaciality in PERC is possible but is not done.
- From a materials production point of view, switching to n-type can be easily done with little additional cost, and is technologically mature, so it is likely to happen.
- N-type cells require mostly the identical manufacturing tools as PERC cells; given the efficiency advantage over PERC, manufacturers are likely to switch.
- Dominance of p-type has historical reasons: when Si cells were used for satellites in the 50s and 60s, p-type cells degraded less quickly in space than n-type cells, so processes on p-type wafers were developed. Now it is time to overcome this historical development and take advantage of n-type.

Watching out for these various aspects and how they develop in the coming years will be important for recognizing trends sufficiently early. And, above all, the PERC cell may be developed into a PERC+ cell by incorporating features from n-type cells such as passivated contacts, hetero-emitters and hetero-BSFs.

Instead of one main workhorse, will we have more

cell concepts coexisting? If so, they would need to converge to very similar efficiencies and fabrication cost to coexist, otherwise one cell concept will be the main workhorse and push out the others to emerging niche markets. The race is on.

Acknowledgements

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