R&D of mass-producible PERC cells with average conversion efficiency over 20%

Wei Shan[1,2], **Xiulin Jiang**[1], **Haibin Yu**[1] and **Yong Liu**[1]

[1]Cell R&D Center, JA Solar Holdings Co. Ltd, Yangzhou, China; [2]JA Solar USA, San Jose, California, USA

ABSTRACT

A recent revitalization of the passivated emitter and rear cell (PERC) concept in the silicon PV industry has resulted in solar energy conversion efficiencies of greater than 20% being achieved on p-type solar-grade single-crystalline silicon (mono-Si) wafers during the past two years or so, thanks to technological advance in the use of aluminium oxide for silicon surface passivation. The research efforts carried out at JA Solar in developing an industry version of PERC cells that can be mass produced utilizing the existing conventional back-surface field (BSF) cell manufacturing platform with moderate retrofitting have yielded 20.5% average conversion efficiency, which can be consistently achieved on p-type Si wafers grown by the Czochralski method. Moreover, the experimental results showed that an average conversion efficiency of 20% is achievable when, in combination with JA Solar's proprietary light-trapping technique, the same technological approach is applied to the cells using high-quality polycrystalline silicon (multi-Si) wafers produced by the seeded directional solidification method.

Introduction

The passivated emitter and rear cell (PERC) – or, strictly speaking, passivated emitter and rear locally diffused (PERL) cell – structure has long been considered capable of yielding high energy conversion efficiency in silicon wafer-based single-junction solar cells [1]. If the metal contact on the full area of the back side of a conventional back-surface field (BSF) cell is replaced with a passivation layer or stack and many small localized contacts, the recombination velocity at the back surface can be greatly reduced, resulting in an enhancement of the spectral response in the long-wavelength region of solar irradiance (low photon energies), which leads to an increase in short-circuit current density. The open-circuit voltage is also increased as a result of increased short-circuit current density and decreased diode recombination current at the back contact [2,3]. By using an oxide passivation layer and locally diffused contacts on the back side, together with inverted pyramids structured on the front surface and a double-layered passivation and anti-reflection coating, Zhao and his co-workers [4] in 1998 demonstrated close to 25% conversion efficiency for such a single-junction PERC solar cell using a p-type float-zone Si wafer.

The advantages of the PERC concept are that, in principle, it does not impose on the wafers the same necessary requirement of high quality as for interdigitated back contact (IBC) and heterojunction with intrinsic thin layer (HIT) cells (see, for example, Maruyama et al. [5] and Mulligan et al. [6], and references therein); more importantly, it can be structured on p-type wafers, from which the vast majority of solar cells have been made in the past, and still are today. However, for many years the industrial adoption of the PERC structure for the mass production of solar cells using silicon wafers has been very limited, primarily owing to the complexity of the use of thermal oxidation to obtain satisfactory passivation quality. Additionally, there are concerns about the creation of local contacts through localized diffusion without significantly degrading the quality of the wafers, as well as the manufacturing cost associated with the cell fabrication process.

> "The PERC concept does not impose on the wafers the same necessary requirement of high quality as for IBC and HIT cells."

On the other hand, aluminium oxide (Al_2O_3 in non-stoichiometric form) for silicon surface passivation was proposed by Jaeger & Hezel [7] nearly three decades ago. Since the demand for lower-cost but higher-efficiency cells has increased in recent years, and the price of silicon wafers has steadily decreased, the effectiveness of Al_2O_3 passivation has been revisited and more extensively studied. A number of research groups have been able to experimentally demonstrate that a thin layer of Al_2O_3 or a dielectric stack of Al_2O_3/SiN_x is very effective and efficient in producing high-quality passivation, especially on p-type silicon surfaces, without the need to subject the Si wafers to a high-temperature thermal oxidation process followed by a forming gas anneal for surface passivation [8,9]. The understanding of the fundamental physics involved in the passivation mechanism of Al_2O_3 on Si surfaces has revitalized PERC R&D activities in the silicon PV community. During the last few years, as innovative high-throughput Al_2O_3 deposition tools specifically designed for PV applications, based on various deposition methods such as spatial atomic layer deposition (ALD) and plasma enhanced chemical vapour deposition (PECVD), have become available and more adaptive to the PV industry, the approach of using Al_2O_3 film for PERC cell back-side passivation has gained considerable momentum (see, for example, Kessels & Putkonen [10] and references therein). All of this has resulted in an accelerated transition of the PERC concept from research laboratory prototypes to industrial solutions for high-performance solar cells.

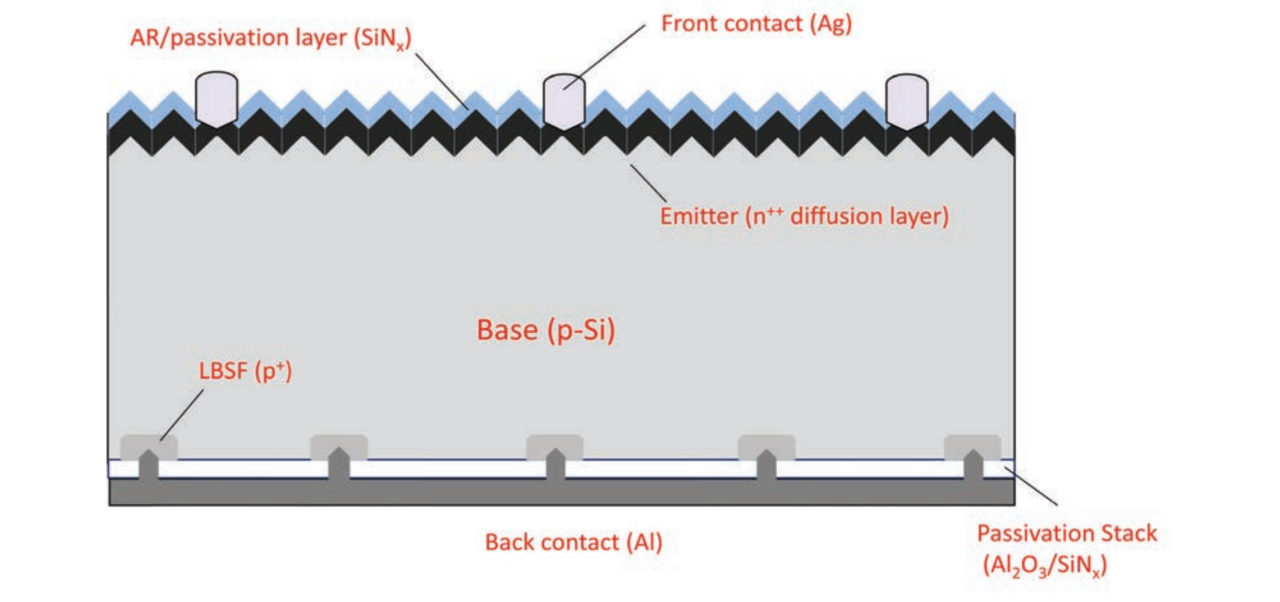

Figure 1. Schematic illustration of the PERC cell structure (not to scale).

In this paper it is shown that, by incorporating a few extra process steps, which include the deposition of an Al_2O_3/SiN_x stack on the back side of Si wafers and the formation of a localized contact pattern by pulsed laser opening, into the mainstream conventional BSF cell manufacturing flow, an average conversion efficiency above 20% for PERC cells can be readily achieved using commercially available p-type mono-Si wafers. In addition, JA Solar's very recent experimental results have demonstrated that, with the implementation of the same technical approach in combination with an advanced light-trapping scheme, a 20% average conversion efficiency can be obtained for PERC cells using casted polycrystalline Si wafers.

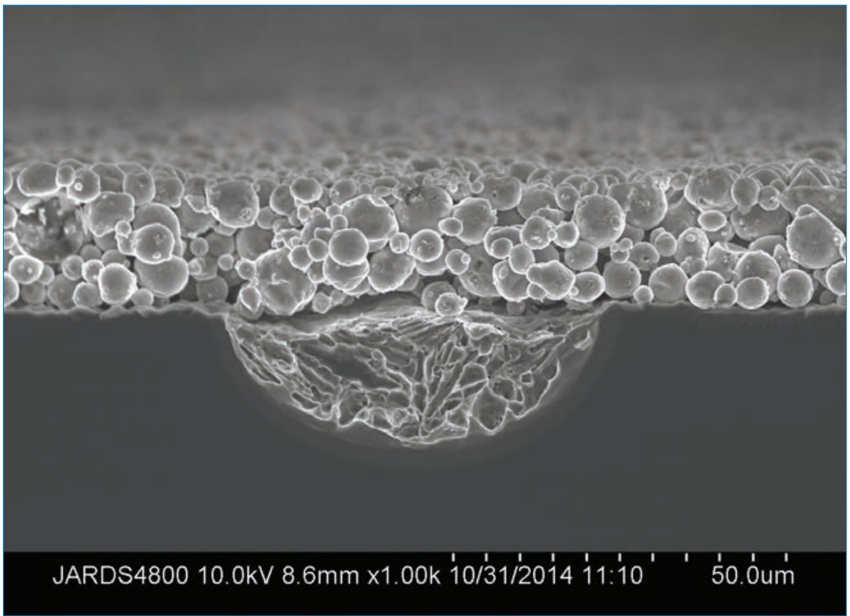

Figure 2. Cross-sectional SEM image of a local BSF formation.

Experimental details

The starting material for PERC cell development was solar-grade silicon wafers, sliced from boron-doped p-type single-crystalline silicon ingots grown by the Czochralski method. The wafers were of a typical industrial size, nominally 156mm × 156mm, with a thickness of 180±10µm and a bulk resistivity in the general range of 1.0–3.0Ω-cm.

A schematic illustration of the device structure of a PERC cell is shown in Fig. 1. The cell structure is basically the same as that of a conventional full BSF cell, apart from the back side. The front side consists of a homogeneous emitter (a heavily doped n^+ layer) formed by doping the silicon with phosphorus through thermal diffusion after the surface is textured by anisotropic etching. On top of the emitter, a thin layer of SiN_x is deposited using the PECVD method to provide anti-reflection and passivation for the front surface; a number of metal (Ag) fingers that make direct contact with the emitter are also deposited. The back side of the cell is covered by a dielectric stack of Al_2O_3/SiN_x, with a fairly thick aluminium layer on top as the current conduction electrode. The dielectric stack is formed by first depositing a very thin (~5–25nm) layer of Al_2O_3 on the bare Si surface using either the ALD or the PECVD method; this is followed by a relatively thick (≥100nm) SiN_x layer deposition using PECVD.

The Al contact to the Si wafer is made through a group of patterned openings on the Al_2O_3/SiN_x stack using a pulsed laser. The predetermined opening pattern dictates that the contacts will be made only through the openings in a controlled manner, and forces the formation of heavily doped p^+ regions to be localized underneath the openings where the Al contacts the Si, thereby creating the so-called local back-surface field (LBSF). In this way, the number of contacts and the total area of metal contacts, as well as the dissolution of Si in Al during metallization (making electrical contacts), can be finely controlled.

The cross-sectional SEM image in Fig. 2 shows the details of such a local contact on the back side of a PERC cell. The thick Al layer was screen printed onto the back surface of the Si. There is no direct contact between the top Al layer and the underlying Si substrate along the interface, because they are separated by an Al_2O_3/SiN_x

stacking layer (too thin to be visible in the image), apart from a bowl-shaped feature protruding into the Si bulk at the location where there is an opening in the dielectric layer. That feature is a typical example of an LBSF formed by a process of Al alloying with Si during a rapid thermal treatment referred to as a 'co-firing process' [11], resulting in low resistive ohmic contact between Al and Si. The co-firing process also brings the Ag fingers that are screen printed on the front surface into intimate contact with the n^+ emitter by punching through the SiN_x layer.

Results and discussion

Both the ALD and PECVD methods were used to deposit aluminium oxide thin film onto the silicon wafer surface. The experimental results showed that the recombination velocity at the back surface can be controlled to well below 100cm/s, with the implied open-circuit voltage (iV_{oc}) ranging from around 680 to 690mV before metallization. Considering the quality of the wafers used in this work, as well as the fact that the size of the textured surface area was much larger than the actual wafer, these numbers are in good agreement with the reported values in the literature [12] (and see, for example, Werner et al. [13] and references therein).

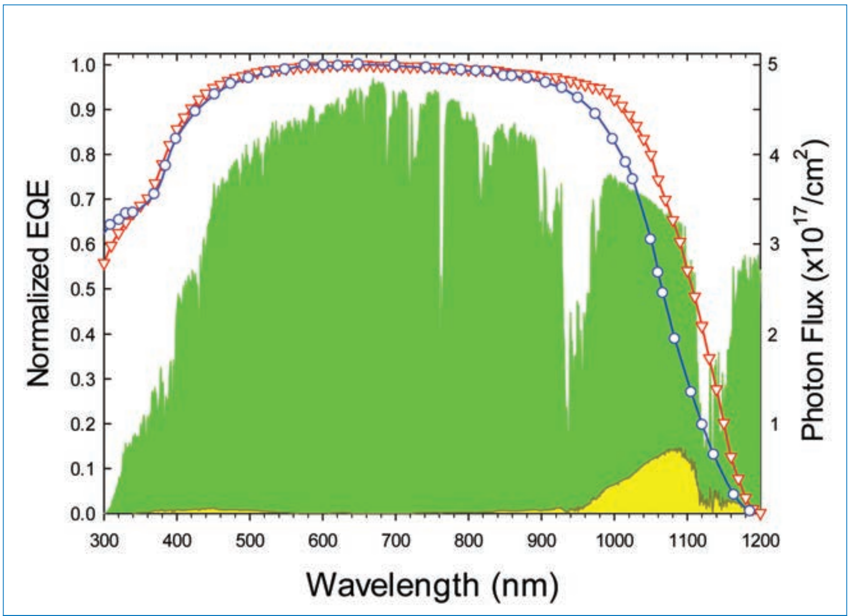

Figure 3. Measured EQE of a 20.25% PERC cell (red triangles/line) compared with that of a 19.1% conventional full BSF cell (blue circles/line). The shaded green area is the photon flux of AM1.5G solar irradiance, and the yellow area represents the net difference between the integrated photon fluxes governed by the EQE of the respective PERC and conventional cells.

Mono-Si PERC cells

Given that the surface recombination velocity at a PERC cell's back surface has been significantly reduced, and that the diode recombination current has been significantly decreased by shrinking the metal contact area from almost 100% of conventional full BSF down to a mere few per cent of localized BSF on the back side, it becomes straightforward to achieve >20% conversion efficiency using commercially available mono-Si wafers, as compared with the baseline of >19% efficiency mono-Si cells with full BSF.

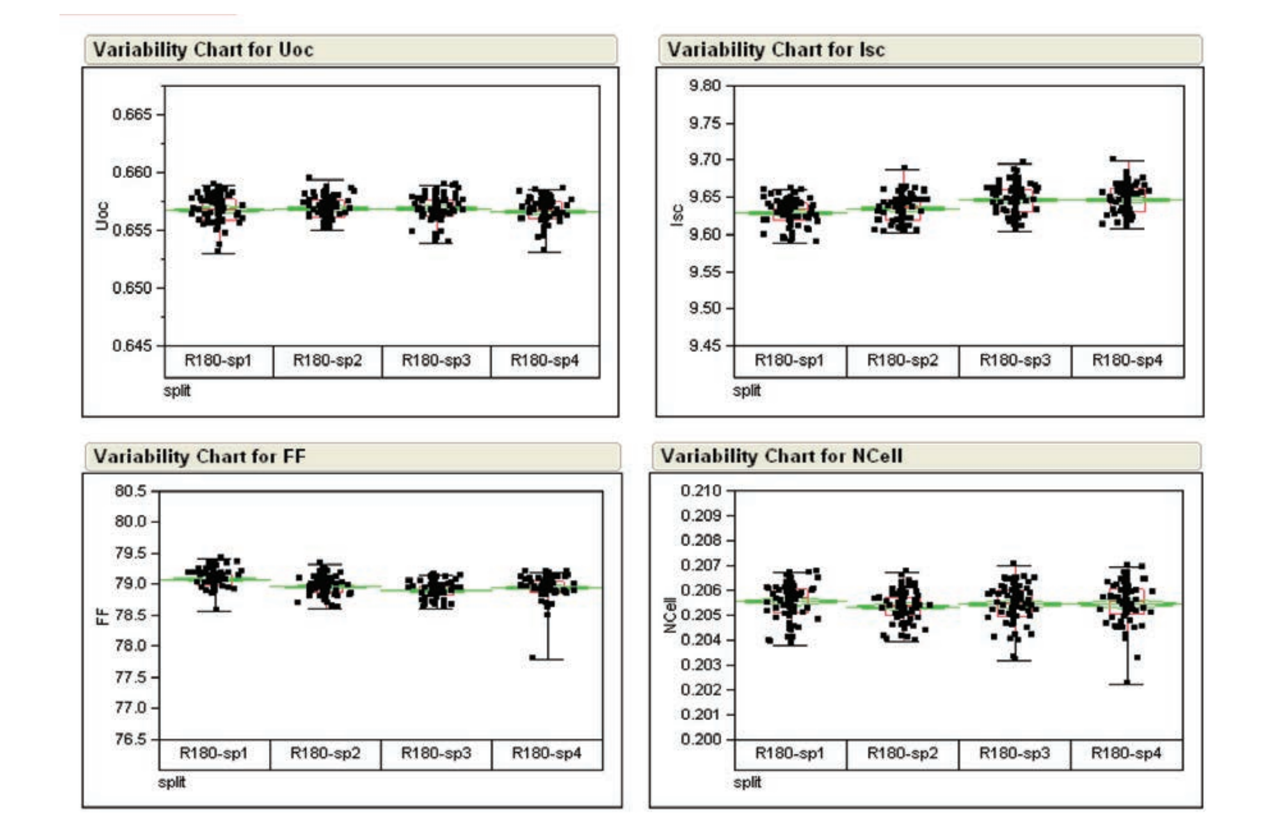

Figure 4. Variations of key cell performance parameters (V_{oc}, I_{sc}, *FF* and η, respectively) from one experimental run. The cells were split equally into four groups and processed under different conditions.

"The much-enhanced spectral response exhibited by the PERC cell in the long-wavelength region in particular is the key factor in boosting cell conversion efficiency."

Fig. 3 shows the measured normalized external quantum efficiency (EQE) of a PERC cell with 20.25% conversion efficiency [14], together with the EQE curve for a full BSF cell with 19.1% efficiency. The green area in the figure is the photon flux of standard solar irradiance (air mass 1.5 global – AM1.5G) as a function of wavelength in the spectral range of the EQE measurements. As can be seen from Fig. 3, while there is not much difference in the EQE between two samples in the short-wavelength region (because the device structures at the front side of both types of cell are the same), the difference in the long-wavelength range is very prominent. The much-enhanced spectral response exhibited by the PERC cell in the long-wavelength region in particular is the key factor in boosting cell conversion efficiency, because more carriers generated by the photons in the spectral range are available for collection as a result of the significant reduction in the recombination of photogenerated carriers in the vicinity of the back surface passivated by Al_2O_3 and in the metal contact areas. The net difference in the photo flux (~9.3×10^{16}/cm^2) corresponding to the greater number of carriers flowing out of the cell in short-circuit connection under one-sun conditions (AM1.5G) is illustrated by the yellow area in the figure. This enhancement in quantum efficiency results in not only a ~1.5mA/cm^2 increase in short-circuit current density (J_{sc}), but also a >10.0mV higher voltage for all the carriers out of the PERC cell. This in turn leads to a gain in efficiency of more than 1% abs. for PERC cells over conventional full BSF cells.

To provide a true picture of industrial R&D results, a set of cell results from one of many experimental runs is shown in Fig. 4: key cell performance parameters – open-circuit voltage (V_{oc}), short-circuit current (I_{sc}), fill factor (*FF*) and conversion efficiency (η) – are displayed in their respective variability charts. In this experimental run, a batch of 400 full-square mono-Si wafers was split equally into four groups and processed under different conditions at certain steps of the cell fabrication procedure. It can be seen from the figure that the conversion efficiency averaged over all the cells in every single group is above 20.5%. Note that, despite each split in this experiment being subjected to slightly different process conditions, they all yield approximately the same conversion efficiency, indicating that the process window for PERC cell manufacturing is fairly large.

Multi-Si PERC cells

Multi-Si wafers produced by the directional casting method have traditionally been regarded as only suitable for making solar cells at a low cost but with mediocre performance because of their relatively low crystal quality. In the past few years, high-quality multi-Si wafers with uniform grain size and low density of dislocations have become commercially available as a result of the recently developed seeded directional solidification method [15–17]. The current consensus in the industry is that the conversion efficiency of solar cells made from these high-quality multi-Si wafers is on average ~0.3–0.5% higher than that for cells using regular multi-Si wafers. For example, in mass production at JA Solar the average conversion efficiency of the cells using such wafers is currently ~18.0±0.1%.

With the 18% efficiency being set as a baseline, the application of the same PERC technical approach as used for mono-Si cells enabled >19.0% average conversion efficiency to be realized in early 2014 from the cells using high-quality multi-Si wafers. In order to further improve cell performance, an advanced proprietary light-trapping approach was developed to overcome the problem of high reflection inherently associated with the acidic textured surface of multi-Si wafers. The average efficiency has gradually been improved since then, with greater than 20% having recently been achieved [18]. Fig. 5 shows a typical *I–V* characteristic taken from one sample out of a batch of such multi-Si PERC cells; its conversion efficiency is 20.1%. The inset in the figure indicates the variation of conversion efficiency from approximately 1600 cells divided equally into four groups. Note that the relatively wide efficiency distribution observed from the finished cells is very typical for multi-Si cells, even with high-quality wafers being used, primarily because of the large variation in crystal quality due to its polycrystalline nature. Nevertheless, the achievement of an average conversion efficiency greater than 20% is quite an accomplishment for the silicon PV industry.

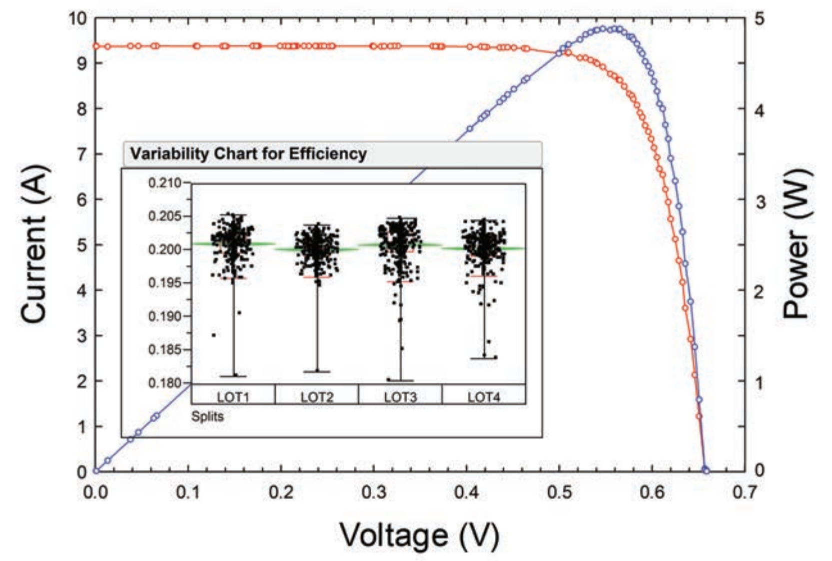

Figure 5. *I–V* characteristic of a multi-Si PERC cell with 20.1% conversion efficiency. The inset shows the distribution of cell conversion efficiency in ~1600 cells divided equally into four groups.

The additional 1% abs. efficiency improvement can be chiefly attributed to the incorporation of a proprietary light-trapping scheme into the multi-Si PERC cell fabrication process; this scheme significantly reduces the reflection from the multi-Si cell surface. Fig. 6 shows the plots of the EQE and reflection curves for the PERC cell, along with those for an 18.0% conventional multi-Si cell. It can be observed that the overall effect of combining the light-trapping scheme with the PERC structure, aided by the presence of a dielectric stack covered by a thick layer of Al on the cell back side, is a vast improvement in the cross-band spectral response, leading to the considerable boost in both I_{sc} and V_{oc} for the cells.

> "The additional 1% abs. efficiency improvement can be chiefly attributed to the incorporation of a proprietary light-trapping scheme."

Concluding remarks

To date, well over 100,000 cells have been fabricated in many experimental runs in order to validate cell design and the corresponding manufacturing process, to simulate mass-production conditions, to verify settings for equipment and tools that are to be retrofitted into the current mass-production manufacturing platform, and, most importantly, to continue to improve the performance and test the reliability of the cells. The industrial version of screen-printed PERC cells reported in this work has been demonstrated to be clearly superior to conventional full BSF cells in terms of cell performance of both single-crystalline (mono-) and polycrystalline (multi-) Si wafers, with greater than 20.5% and 20.0% average conversion efficiencies, respectively, being realized.

The PERC cell process with the addition of a dielectric Al_2O_3 passivation layer or Al_2O_3/SiN_x stack on the back side of a Si cell, and a structuring of localized contacts (LBSF) through laser opening, does not require p-type wafers of the highest quality in order to achieve more than a 1% gain in efficiency. Furthermore, the process can be implemented on a conventional Si solar cell manufacturing platform without significantly changing the cell process flow. It is important to note that, especially when concerns about the costs of manufacturing wafer-based Si cells need to be addressed, the cell process window is opened up considerably by obtaining an excellent passivation effect from Al_2O_3 without subjecting the Si wafers to high-temperature thermal oxidization to achieve the required passivation effect. The approach of using short-pulse laser ablation to form contact openings is fully compatible with the screen-printing-based cell manufacturing platform. Of course, the choice of the right deposition method and equipment, including laser ablation tools, and their coherent integration into existing cell manufacturing lines, as well as the set-up of optimized process parameters, are all of vital importance in making PERC cells mass producible. Fortunately, the success of this has been made much easier by the recent rapid progress in the development and commercialization of high-throughput Al_2O_3 deposition equipment and pulsed laser processing tools.

> "The implementation of the PERC device structure into mainstream p-type Si solar cells is expected to be a prevailing technological trend in the next few years."

Finally, it has to be pointed out that more than 90% of the PV modules produced today worldwide are based on crystalline silicon wafer technologies. Approximately 35–40% of these modules are based on single-crystal silicon grown by the Czochralski pulling process, and 60–65% are based on polycrystalline ingots cast in crucibles by directional solidification. Among these modules, over 95% are assembled by p-type wafer-based Si cells and dominate the global production of solar electricity. Therefore, as the performance of PERC cells is continually being improved, the

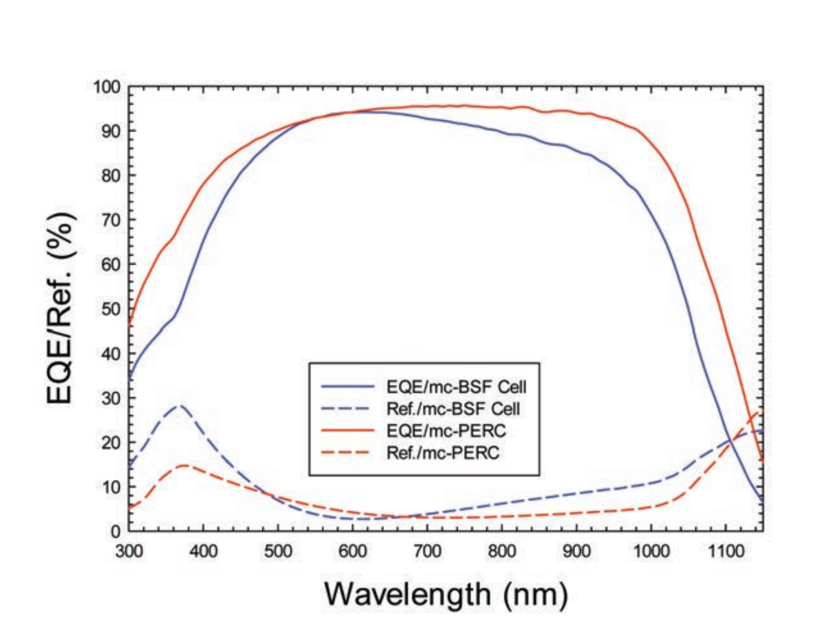

Figure 6. Comparison of the EQE and reflection of an 18.0% conventional multi-Si cell (mc-BSF cell, blue lines) and a 20.1% multi-Si PERC cell (mc-PERC, red lines).

implementation of the PERC device structure into mainstream p-type Si solar cells is expected to be a prevailing technological trend in the next few years.

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About the Authors

Dr. Wei Shan has been with JA Solar since 2008 and is currently the chief scientist and head of R&D. With more than 30 years' experience in R&D in a wide variety of semiconductor material systems and devices, he has published over 150 peer-reviewed journal articles and prestigious conference papers, as well as six book chapters.

Xiulin Jiang studied materials physics at the University of Science and Technology of Central China. He has been working in the Research and Development Center at JA Solar since 2007.

Haibin Yu studied control technology and instrumentation at the University of Science and Technology of Qingdao, China, where he received his bachelor diploma in 2005 and completed his master's in 2010. He has been working at JA Solar's Research and Development Center since joining the company in 2008.

Yong Liu has been with JA Solar since 2008 and is the chief technology officer. He has many years of experience in the semiconductor IC chips manufacturing sector and expertise in leading technology development. He also currently serves as JA Solar's chief operations officer.

Enquiries

Wei Shan
Cell R&D Center
JA Solar Holdings Co. Ltd
1 Jianhua Road
Yangzhou
225000 Jiangsu
China

Tel: +86 (514) 8554 8278
Email: weishan@jasolar.com
Website: www.jasolar.com