Technical progress in high-efficiency solar cells and modules

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ABSTRACT

This paper focuses on the technical progress of high-efficiency crystalline silicon solar cells and modules, specifically with regard to passivated emitter and rear cell (PERC) processes, module description and light-induced degradation (LID) data. Through appropriate optimizations of the solar cell and module processes, the cell efficiency achieved in mass production is 21.3%, with module power exceeding 300W. To solve the LID problem, hydrogenation technology developed by UNSW is used, bringing the cell LID rate down to below 1%.

Introduction

The passivated emitter and rear cell (PERC) concept was developed at the University of New South Wales (UNSW) over 25 years ago [1]. There are complications, however, when transferring the laboratory PERC solar cell process sequence to an industrial manufacturing setting. The focus will therefore be on simplifying the process sequence for industrial implementation, but aiming to obtain the same solar cell conversion efficiency as in the laboratory. In the manufacture of PERC solar cells, plasma-enhanced chemical vapour deposition (PECVD) is used to form the passivation layer, and laser opening contact is employed on the back surface. At the same time, integrated module technologies are used in order to achieve high module power.

The boron–oxygen (B–O) defect is a major concern to the PV community: it can reduce the efficiency of p-type Czochralski (Cz) silicon PERC solar cells by up to 2%$_{abs.}$ compared with the efficiency measured at the end of fabrication. In order to reduce the light-induced degradation (LID) of Cz PERC cells, hydrogenation technology developed by UNSW is used in Suntech's production line.

Solar cells

Commercial-grade boron-doped Cz p-type silicon wafers are used in the development of PERC solar cells at Suntech; the Cz-Si wafer specification is resistivity 1–3Ω·cm, thickness 200μm and size 156mm × 156mm. Solar cells are fabricated using the PERC processing sequence, as shown in Fig. 1. Prior to the deposition of the dielectric passivation layers, wafers are saw-damage etched and surface textured by KOH solution, followed by HCl/HF cleaning, phosphorus diffusion and edge etching. The sheet resistance of the emitter is ~90Ω/sq. An AlO_x layer is deposited using standard Roth&Rau remote microwave PECVD systems, and SiN_x layers are deposited using Centrotherm direct PECVD systems. The hydrogenation process takes place after printing and firing.

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To improve solar cell efficiency, the diffusion and screen-printing processes are optimized once the PERC solar cell process sequence has been confirmed. An optimization of the diffusion process is first performed in order to obtain a low surface concentration and a deep junction depth. The best result achieved is a surface concentration of $2\times10^{20}/cm^3$, with a corresponding junction depth of 0.4μm. The efficiency can be increased by 0.15%$_{abs.}$; this increase can be attributed to the improvement in quantum efficiency

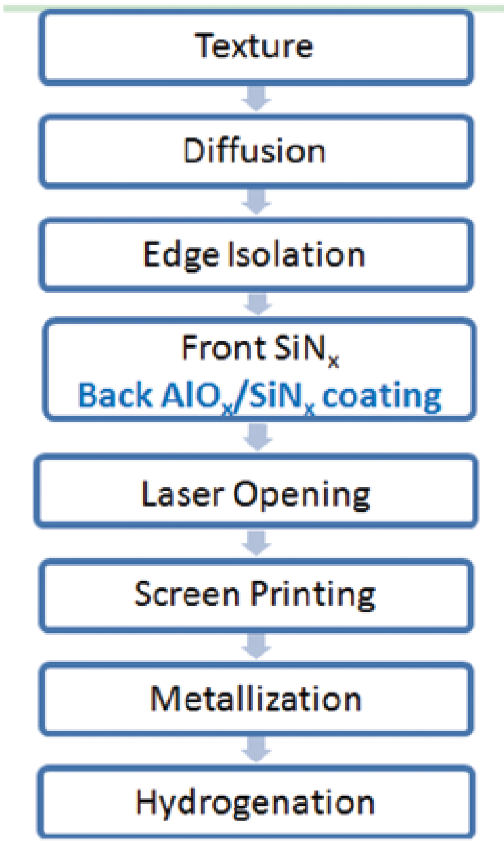

Figure 1. Process sequence for PERC solar cells.

(QE) at short wavelengths. The QE curve after the diffusion optimization is shown in Fig. 2.

The laser process, the selection of the Al paste, and the firing process are three of the most critical aspects of PERC production. The line width resulting from the laser opening, the number of lines, and the depth of the local back-surface field (LBSF) all influence the open-circuit voltage (V_{oc}), series resistance and fill factor (FF). The width and number of laser lines can be synthetically regarded as the surface proportion of the laser opening; on the basis of a series of experiments, the optimized opening proportion should be around 5.5%. In order to yield a satisfactory filling of the Al paste, the width of the lines is controlled to around 50µm. A deeper LBSF can exhibit a higher V_{oc} and FF; the depth of the LBSF is over 5µm as a result of improving the Al paste and firing process. Figs. 3 and 4 show the profile of the laser opening line and a scanning electron microscope (SEM) image of the LBSF respectively.

When all the above-mentioned optimized conditions are incorporated, the daily average efficiency achieved in mass production is over 21%. A cell selected from Suntech's PERC mass production line, not from the laboratory, yielded a maximum efficiency of 21.31% (Fig. 5), as documented in the measurement report from China PV Test Center (CPVT).

Solar cell LID

The properties and interactions of hydrogen in silicon have been extensively studied over many decades, with the beneficial effects shown as early as 1976 [2]. The use of hydrogen-containing anti-reflection coatings (such as PECVD SiN), particularly in the fabrication of multicrystalline silicon solar cells, is essential for bulk and surface passivation [3]. For monocrystalline silicon, recent studies have shown that hydrogen plays a critical role in the permanent deactivation of B–O complexes [4–5].

Hydrogen has been shown to be highly reactive, with the ability to interact with the silicon lattice and with virtually all impurities and defects within the silicon [6]. Subsequently, hydrogen passivation has been demonstrated to allow substantial improvements to the electrical performance of silicon solar cells through the deactivation of recombination activity associated with a wide array of structural- and impurity-related defects in these cells [3,4,7,8].

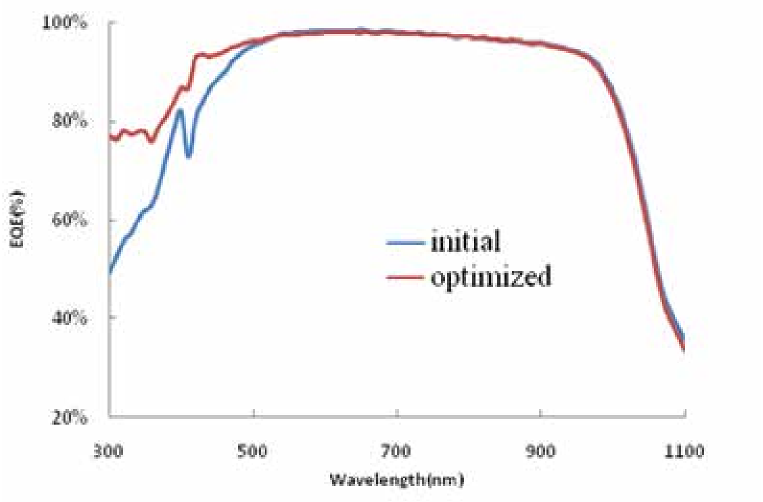

Figure 2. QE curve before and after optimization of the diffusion process.

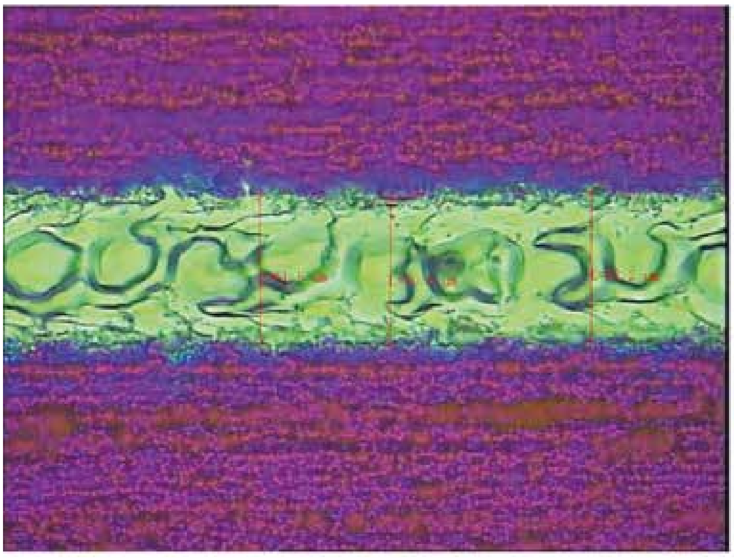

Figure 3. Profile of the laser opening line.

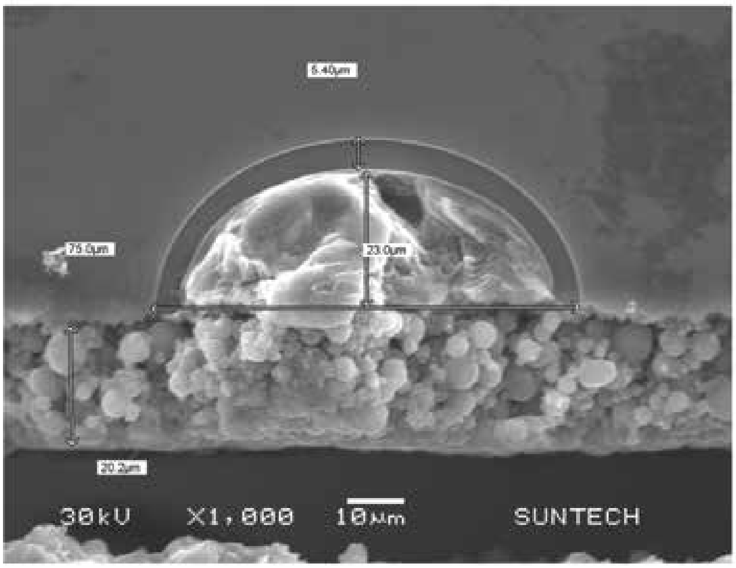

Figure 4. SEM image of the LBSF.

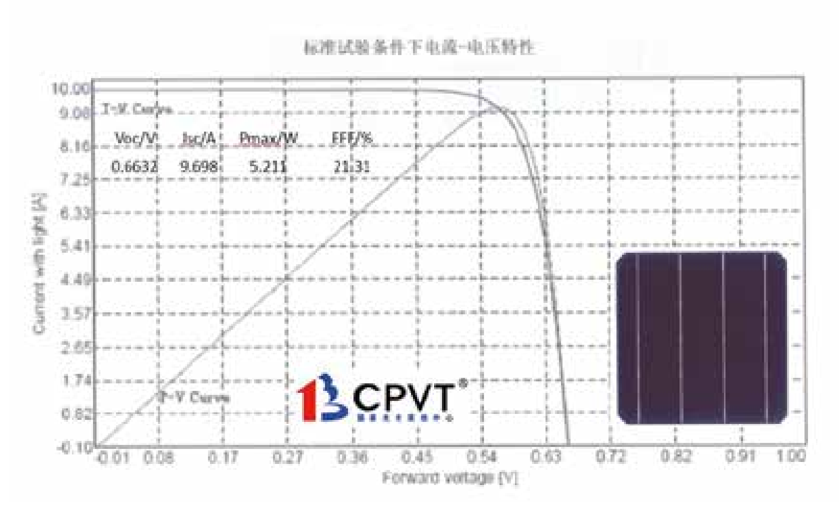

Figure 5. Cell test report from CPVT for Suntech's PERC mass production line.

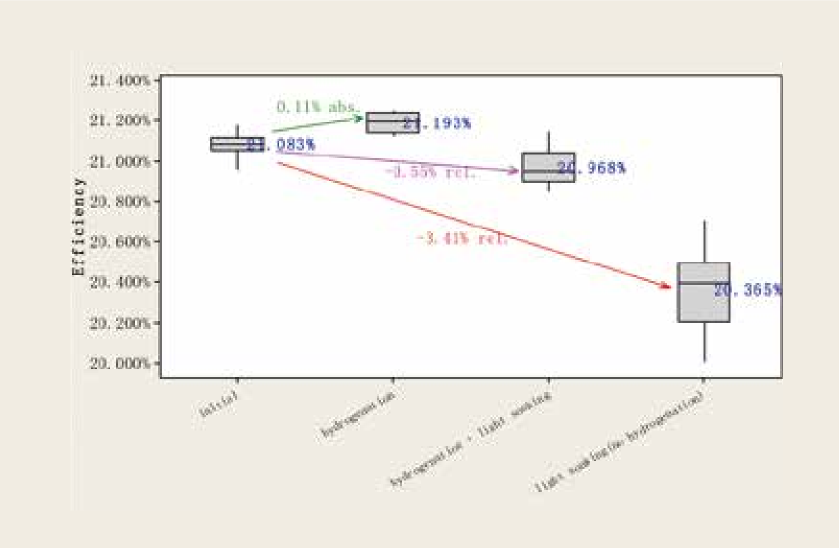

Figure 6. Effects of hydrogenation (light-soaking conditions: Xe lamp, 1kW, 5h @ 45°C).

Hydrogen is a 'negative-U' impurity in silicon with the ability to assume different charge states, taking on a positive (H^+), neutral (H^0) or negative (H^-) charge state [9]. The charge states of the interstitial hydrogen have important implications for both the diffusivity and the ability to interact with defects and impurities within the silicon [9]. For example, deep-level monovalent defects in crystalline silicon solar cells, including interstitial iron (Fe^+), interstitial chromium (Cr_i^+) and the B–O$^+$ complex, have been reported to need H^- for defect passivation [9].

The effects of hydrogenation are shown in Fig. 6: hydrogenation yields a stable increase in efficiency of 0.1%$_{abs.}$, with only a 0.55%$_{rel.}$ efficiency decrease after light soaking. Without hydrogenation, after light soaking there is a 3.41%$_{rel.}$ degradation in efficiency.

> "Hydrogenation yields a stable increase in efficiency of 0.1%$_{abs.}$, with only a 0.55%$_{rel.}$ efficiency decrease after light soaking."

Undoubtedly, a number of B–O complexes are formed during cell fabrication; these are induced by hot carriers, since several high-temperature processes exist. The initial efficiency is limited by these B–O complexes, but hydrogen gives a perfect passivation in the bulk of the wafers, and increases the efficiency. The lifetime scanning maps of the cells before and after

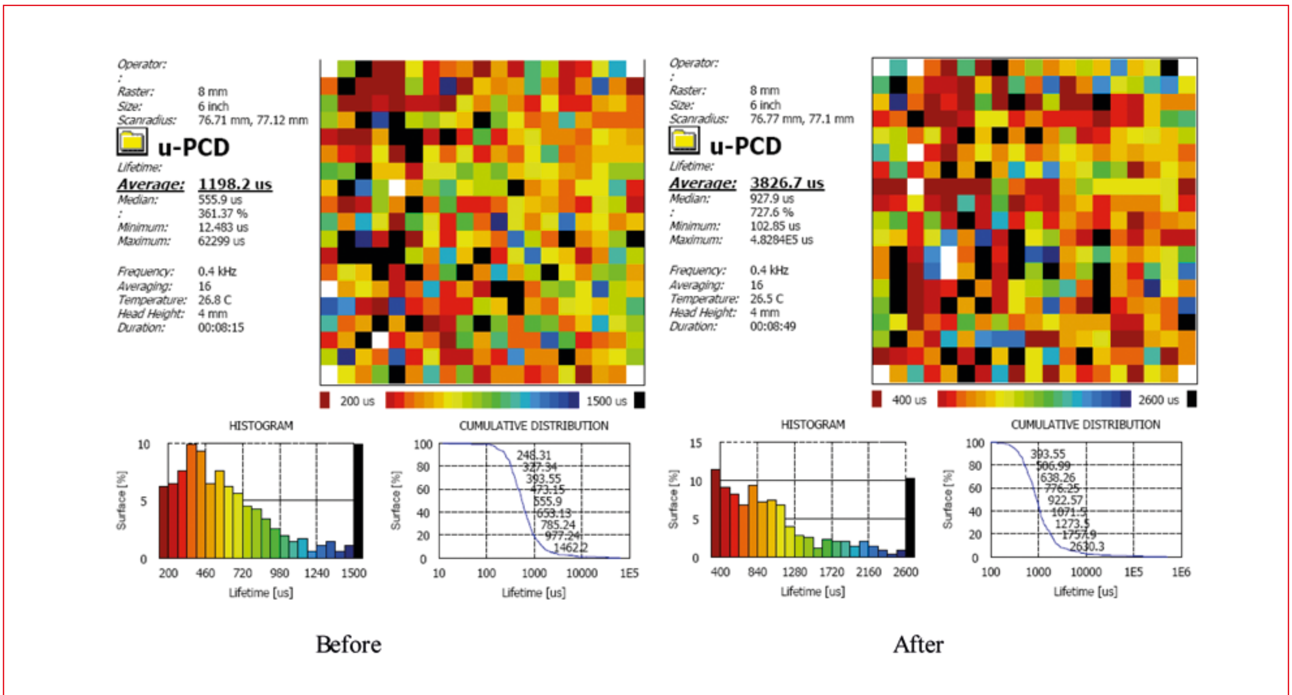

Figure 7. Lifetime scanning map before and after hydrogenation.

hydrogenation are shown in Fig. 7; hydrogenation results in a significant increase in lifetime, and generates an increase in cell efficiency.

Fig. 8 shows the daily average efficiency recorded for Suntech's PERC mass production line. It is clear that the efficiency increase after hydrogenation is stable in actual cell production.

Light soaking was carried out over a long duration in order to observe the stability of the hydrogenation process; Fig. 9 shows the process to be perfectly stable.

Modules

Module technology improvements are also implemented, to complement the Suntech high-efficiency PERC cells and to achieve a higher output power.

As noted earlier, the optimization of the diffusion improves the quantum efficiency at short wavelengths; a high-transmittivity of EVA and glass at short wavelengths is therefore required in order to benefit from cell improvements. In addition, at long wavelengths PERC cells demonstrate a higher response than standard-structure Al-BSF cells; thus, in order to carry through this advantage of PERC cells, EVA and glass with high transmittivity at long wavelengths are also necessary.

New types of EVA and glass have been chosen, with transmittivity curves as shown in Figs. 10 and 11.

When all optimizations are incorporated, the output power of the PERC modules increases by over 5W, with an average daily output power of 295.8W. The power distribution of Suntech's PERC modules in December 2016 is shown in Fig. 12; the measurement report from CPVT notes a maximum power of 303.4W (Fig. 13).

Outdoor module LID measurements have also been carried out. After two months' light soaking (summer 2016, July and August, in Wuxi, China), the degradation in module power is only $2\%_{rel.}$ (Table 1). The electroluminescence (EL) images show very little change after this long period of light soaking (Fig. 14). All the cells therefore demonstrate stable performance in an outdoor environment.

"The daily average output power of the mass production PERC module, incorporating high-transmittivity EVA and glass, was 295.8W, with the power exceeding 300W in a number of cases."

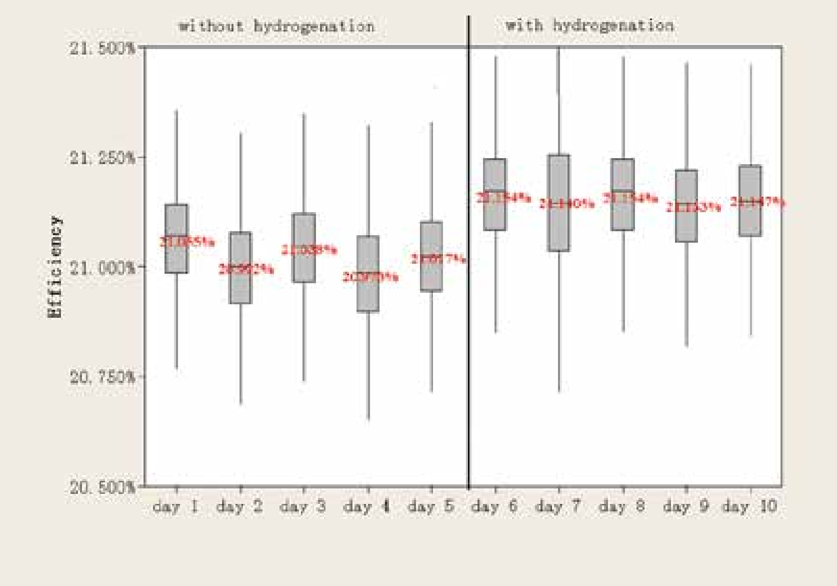

Figure 8. Comparison of data over 10 days for mass production without and with the use of hydrogenation.

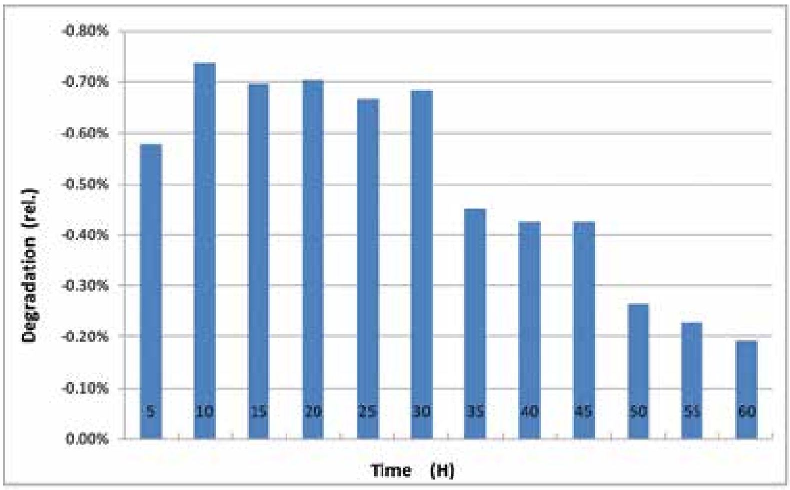

Figure 9. Long-duration light-soaking performance after hydrogenation.

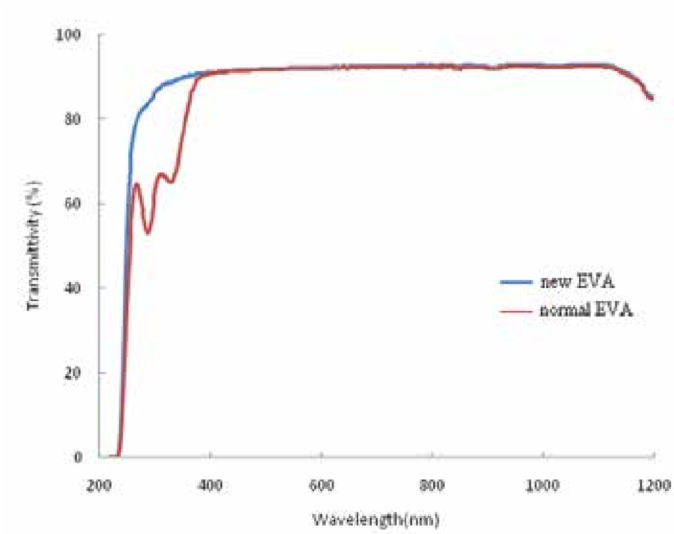

Figure 10. Transmittivity curve of the new type of EVA used for PERC module production.

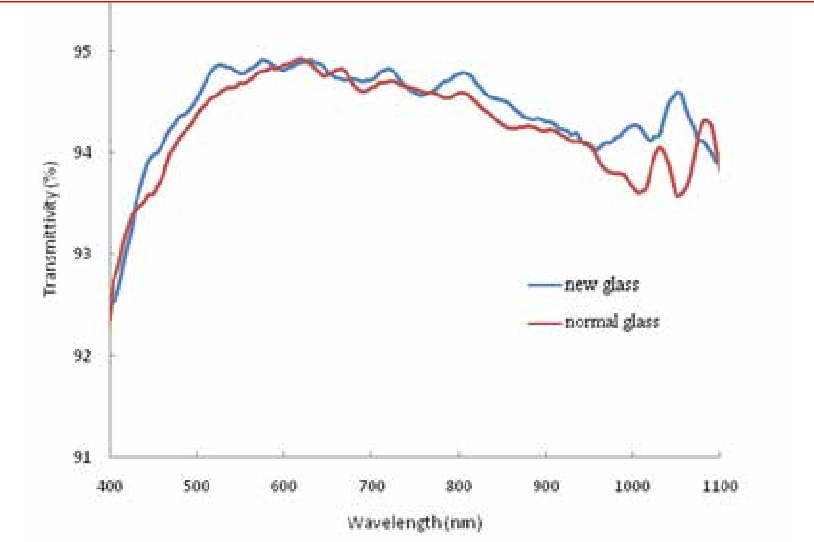

Figure 11. Transmittivity curve of the new type of glass used for PERC module production.

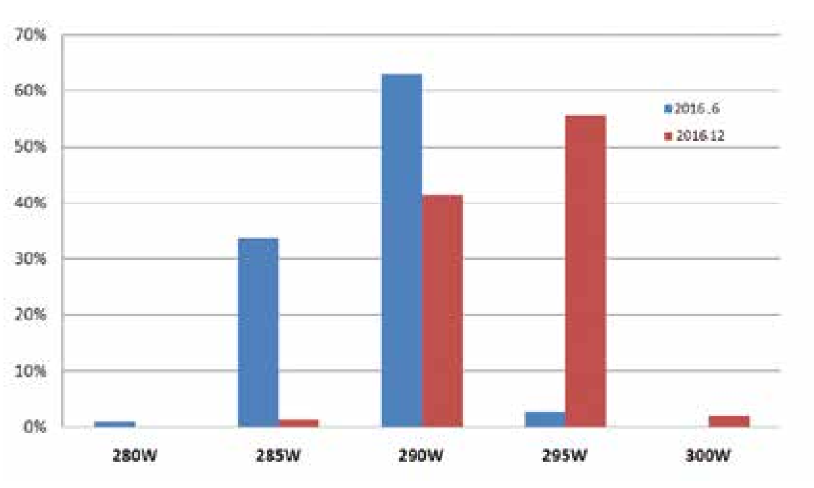

Figure 12. Power distribution of Suntech's PERC modules in December 2016.

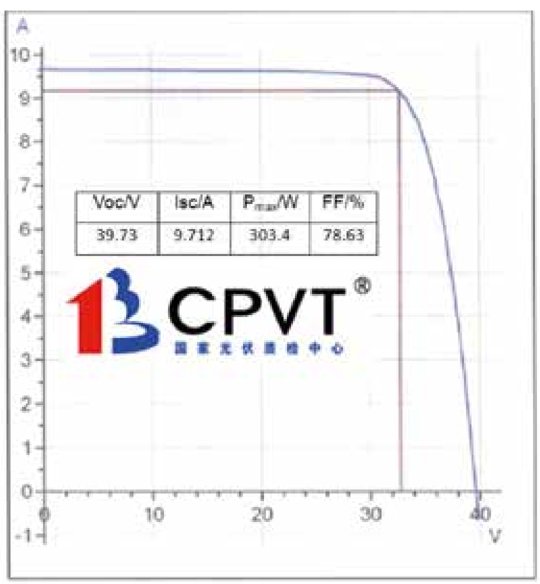

Figure 13. Module test report from CPVT for Suntech's PERC mass production line.

Conclusions

This paper has focused on the technical progress of high-efficiency crystalline silicon solar cells and modules, specifically the PERC solar cell process, module description and LID data. As a result of optimizing the diffusion, laser opening, Al paste selection and firing, as well as improving the passivation layers, the daily average efficiency of cells in mass production was improved to more than 21%. A major general concern in the PV domain, light-induced degradation is especially serious in the case of high-efficiency PERC cells; however, hydrogenation can completely overcome the issue of LID in cells. In Suntech's PERC production line, a gain of $0.1\%_{abs.}$ efficiency was observed after hydrogenation; moreover, an efficiency decrease of less than $1\%_{rel.}$ was recorded after light soaking (Xe lamp, 1kW, 5h @ 45°C).

In respect of modules, the daily average output power of the mass production PERC module, incorporating high-transmittivity EVA and glass, was 295.8W, with the power exceeding 300W in a number of cases.

Acknowledgements

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		V_{oc} [V]	I_{sc} [A]	P_{mpp} [W]	V_{mpp} [V]	I_{mpp} [A]	FF [%]	P. degr. [%]
1	Initial	39.17	9.38	287.48	32.42	8.87	78.2	–2.09
	After	39.07	9.24	281.48	31.99	8.8	77.99	
2	Initial	39.17	9.4	288.08	32.41	8.89	78.22	–1.81
	After	39.09	9.33	282.88	32.06	8.82	77.58	
3	Initial	39.18	9.4	287.29	32.42	8.86	78.03	–1.76
	After	39.13	9.28	282.22	32.03	8.81	77.77	

Table 1. Outdoor module LID measurement data – two months' light soaking (July and August 2016) in Wuxi, China.

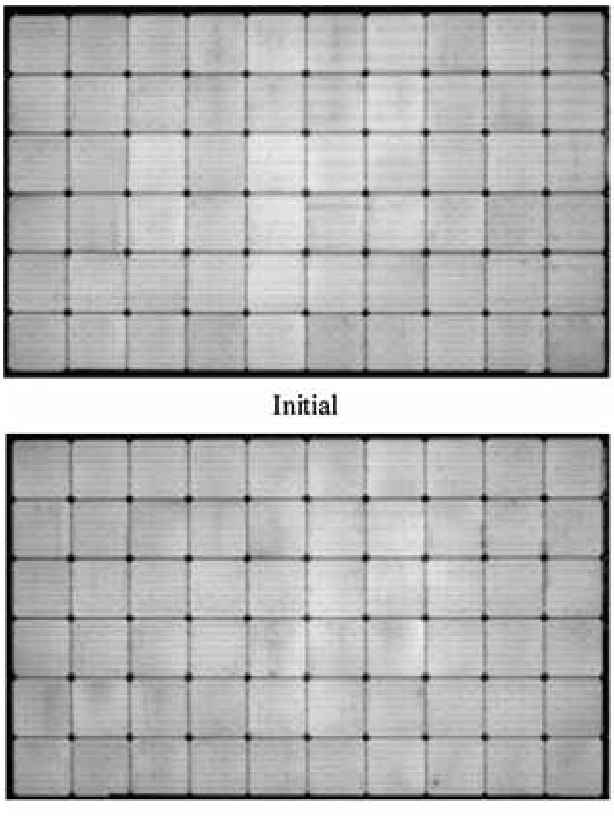

Figure 14. EL images taken before and after two months' light soaking.

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