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Development of cost-effective PERL-type Si solar cells with 19.5% average efficiency

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ABSTRACT

The development of a cost-effective and industrially up-scalable process for p-type Cz monocrystalline silicon solar cells of the passivated emitter, rear locally diffused (PERL) type requires a careful trade-off between the potential benefits that novel process steps can deliver (in terms of improved efficiency and/or process control) and the additional costs involved. The approach chosen by Photovoltech is to limit as much as possible the number of PERL-specific process steps and to fine-tune the processes already in use for our standard full Al back-surface field (Al-BSF) technology in order to satisfy the more stringent requirements of PERL technology. Some of the results of this development are reported in this paper. In particular, the impact of different local BSF pastes on our proprietary extended laser ablation (ELA) rear-contacting technique is investigated, as well as the effect of the wafer resistivity and emitter diffusion/oxidation processes on cell performance. This paper also reports the results of large-batch experiments in which the capability of our optimized PERL process was tested against that of a standard full Al-BSF process. An average efficiency of 19.5% and a top efficiency of 19.7% were demonstrated.

Introduction

Laboratory-scale passivated emitter, rear locally diffused (PERL) solar cells still hold the world record of 25% efficiency for monocrystalline silicon when using a single junction [1–3]. However, almost fifteen years after its first realization, the industrial production of this cell architecture remains challenging. One reason why the widespread industrialization of PERL technology is hampered is the immediate cost issue arising from an increased number of production steps and from the novel type of equipment needed compared to that for the mainstream full Al-BSF-type architecture. This imposes severe requirements not only on the minimum efficiency that PERL cells should have in order to be an economically viable alternative to full Al-BSF cells, but also on the stability throughput and controllability of the new equipment/processes required for PERL cell manufacturing.

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Moors et al. [4] reviewed the efforts made by Photovoltech to speed up the industrialization of PERL-type cells. In particular, a new rear-contacting technique (called extended laser ablation, or ELA) was presented; the method results in a high-quality local back-surface field (BSF) around the rear contacts, allowing a best cell efficiency of above 19% to be realized for PERL cells. These results were obtained while keeping a standard design on the front side (homogeneous emitter; 75Ω/sq; SiN_x anti-reflective coating; screen-printed contacts), using only thin dielectric layers on the rear (~100nm AlO_x/SiN_x stack), and avoiding both the expensive cleaning steps and the final forming gas anneal treatment (FGA) often used for cells with a passivated rear side to heal laser damage and recover high V_{oc} values [5].

This paper reports on the further industrialization of Photovoltech's industrial PERL-type Si solar cells. In particular, a possible path towards higher efficiency and increased manufacturability will be explored by (i) fine-tuning the wafer resistivity; (ii) screening the local BSF paste most suitable for our ELA metallization scheme; and (iii) optimizing the emitter diffusion/oxidation processes. Finally, the capability of Photovoltech's optimized PERL process is tested against that of a standard full BSF process in large-batch experiments. A top efficiency of 19.7%, a 19.5% average efficiency and an efficiency increase of about 1% abs. with respect to Al-BSF cells are demonstrated.

Experimental

PERL cells were fabricated on 156mm×156mm, 200μm-thick, p-type Cz monocrystalline silicon wafers, with resistivity in the 1.5–2.2Ωcm range, according to the industrial process flow: alkaline texturing, single-side polishing, homogeneous emitter (65–77Ω/sq) and wet edge isolation (WEI). After emitter diffusion and WEI, a thin, dry oxide layer was grown in a classic tube furnace; this was immediately followed by AlO_x and SiN_x depositions on the rear (~100nm AlO_x/SiN_x stack) and SiN_x ARC deposition on the front. High-throughput deposition tools were used for this purpose (Roth & Rau PECVD for SiN_x and Levitech Spatial ALD for AlO_x [6]).

Screen printing was used for both front and rear metallization (commercial Ag and Al pastes), followed by a standard co-firing step in an IR belt furnace. A full Al layer was printed on the rear. Rear-side metallization was performed using the ELA process as described in Moors et al. [4]. No FGA was carried out after the ELA process. For the ELA process, a disk laser (60W and ~1μs pulse length) was used (λ = 1032nm). A matrix of dots with a pitch varying from 0.45mm to 0.55mm, depending on the wafer resistivity, was used as the rear-contact pattern for every cell.

Cells were finally characterized by photo- or electroluminescence and quantum efficiency measurements using commercially available systems. The electrical performance was measured using stabilized reference cells calibrated at ISE CalLab and a DC solar simulator under standard illumination conditions (AM 1.5G, 1000W/m², 25°C).

Results

Effect of the wafer resistivity

To increase the efficiency of PERL cells, one option is to reduce the wafer resistivity. For example, Fig. 1 shows that by decreasing the resistivity from 2.2Ωcm to 1.5Ωcm, with all the other parameters

remaining the same, there is an increase of 4.2mV in V_{oc}. Moreover, the lower resistivity allows a further optimization of the rear-contact pitch, which results in a higher fill factor *FF* (Fig. 2).

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A disadvantage of the lower resistivity, however, is that the higher boron concentration can enhance the light-induced degradation (LID) of the cell. For example, at a resistivity of 1.5Ωcm, a drop in efficiency of up to 0.7% is caused by LID, as can be seen in Fig. 3. However, as demonstrated in this figure, a 30-minute anneal at 170°C under 1 sun illumination is sufficient to almost completely recover the cell performance, bringing the boron–oxygen-related complex to the inactive state as described in Rein et al. [7].

Screening of local BSF pastes for the ELA metallization scheme

A critical aspect of PERL architecture is the quality of the local BSF formed around the rear contacts. An insufficient local BSF formation would in fact cause increased recombination and parasitic shunting in the presence of inversion layer passivation at the rear contacts [7]. The selection of the most appropriate local BSF paste is therefore of primary importance for achieving a stable and efficient PERL process. As an example, three different pastes are compared in Fig. 4. From the data reported in the figure it is clear that the best choice for our ELA process would be paste B, which provides the highest values of both V_{oc} (Fig. 4(a)) and J_{sc} (Fig. 4(b)), thus resulting in an overall better efficiency (Fig. 4(c)).

It is interesting to note that paste C performs just as well as paste B with respect to local BSF formation (both achieve a similar V_{oc}), but it is significantly worse in terms of internal reflectance (Fig. 5) and therefore in terms of short-circuit current (Fig. 4(b)). Additional experiments suggest that such deterioration of

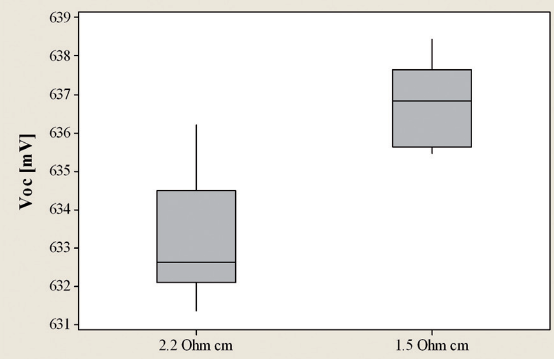

Figure 1. Comparison of the open-circuit voltage for PERL-type Si solar cells fabricated on 2.2Ωcm and 1.5Ωcm substrates. The rear-contact pitch is 0.4mm.

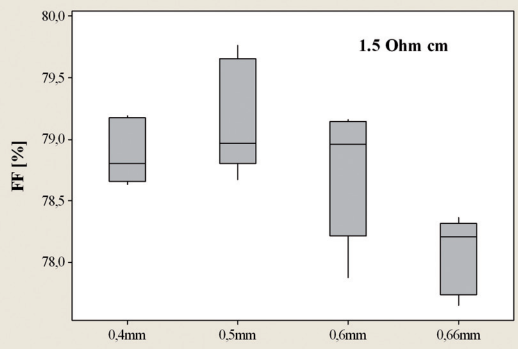

Figure 2. Fill factor as a function of rear-contact pitch, for PERL-type Si solar cells fabricated on 1.5Ωcm substrates.

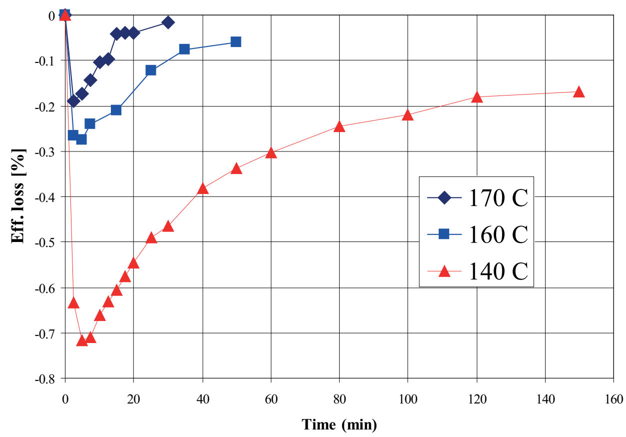

Figure 3. Efficiency loss as a function of exposure time and substrate temperature, during light-soaking (1 sun) for PERL-type Si solar cells. Cells are fabricated on 1.5Ωcm substrates.

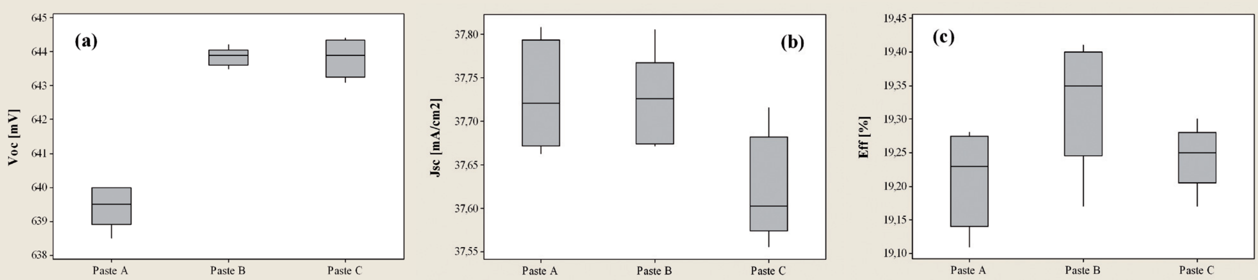

Figure 4. Comparison of PERL-type Si solar cells with three different local BSF pastes: (a) open-circuit voltage; (b) short-circuit current density; and (c) efficiency. The rear-contact pitch is 0.5mm.

internal reflectance would not occur if rear-passivation stacks thicker than our ~100nm-thick AlO_x/SiN_x stack were used, indicating that thin rear-passivation stacks are more demanding with respect to local BSF pastes than thicker ones.

Optimization of emitter diffusion/ oxidation

In Photovoltech's process flow a short oxidation is carried out after the wet edge isolation step. This oxidation step increases the stability and manufacturability of the PERL process, but at the expense of a reduced cell current if the oxide at the front surface is grown too thick [8]. A trade-off between oxide thickness and good rear-side passivation could improve the cell efficiency without jeopardizing the manufacturability of the PERL process. An example of this optimization is shown in Fig. 6. In this figure the effects on the short-circuit current of two different diffusion processes for different oxidation conditions are compared. Clearly, by changing the diffusion process and by reducing the oxidation time, both an increase in J_{sc} (Fig. 6(a)) and good rear-side passivation (higher V_{oc} values in Fig. 6(b)) can be obtained.

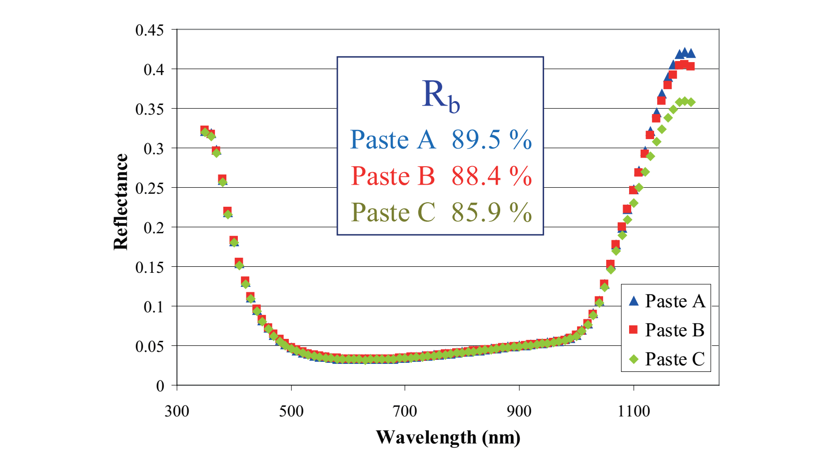

Figure 5. External reflectance measured on the same cells as in Fig. 4. The insert shows the internal reflectance (R_b) of the Si/dielectric/metal system for the three pastes.

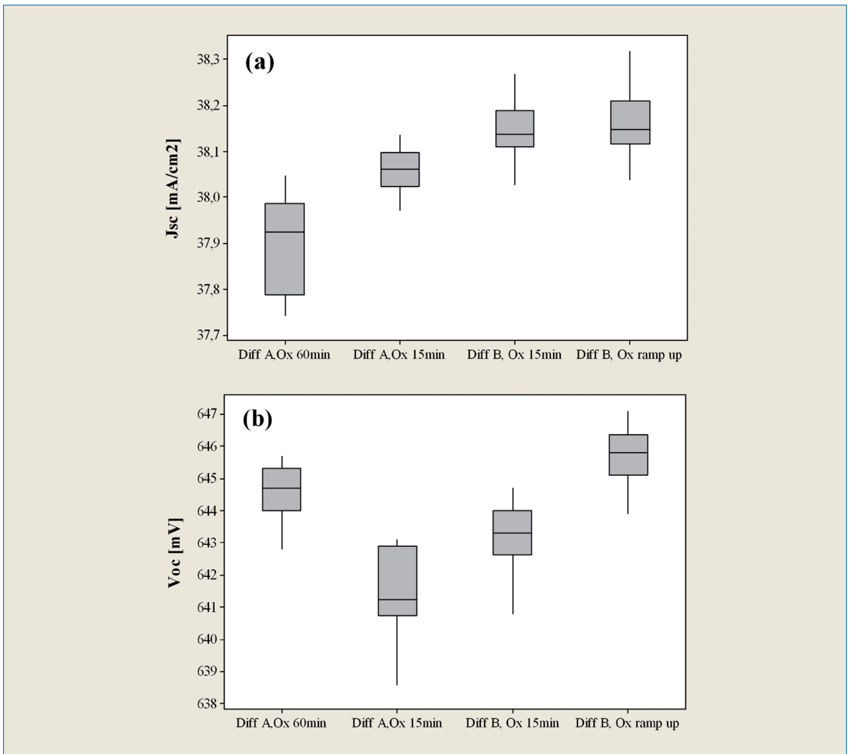

Figure 6. Comparison of PERL-type Si solar cells with different emitter diffusions and oxidation steps: (a) short-circuit current density; and (b) open-circuit voltage. ('60 min' = 60-minute dry oxidation at 800°C, '15 min' = 15-minute dry oxidation at 800°C, 'ramp up' = oxygen flow only during temperature ramp-up.)

Al-BSF versus PERL

After integrating the process optimizations described in the previous sections in the reference PERL-type process flow, large-batch experiments were carried out to benchmark the optimized PERL process with the reference full Al-BSF flow. The results of these experiments are given in Fig. 7 and Table 1. An average efficiency of 19.5% (with 30% of the manufactured cells having an efficiency greater than 19.5% and a maximum of 19.7%) was obtained for the PERL-type Si solar cells. This is about 1% higher than the efficiency obtained for full Al-BSF cells. Moreover – and this is very important for large-scale manufacturing – the spread of the cumulative distribution of PERL and BSF cells is similar, demonstrating a good control of the extra process steps required to manufacture the PERL-type cells.

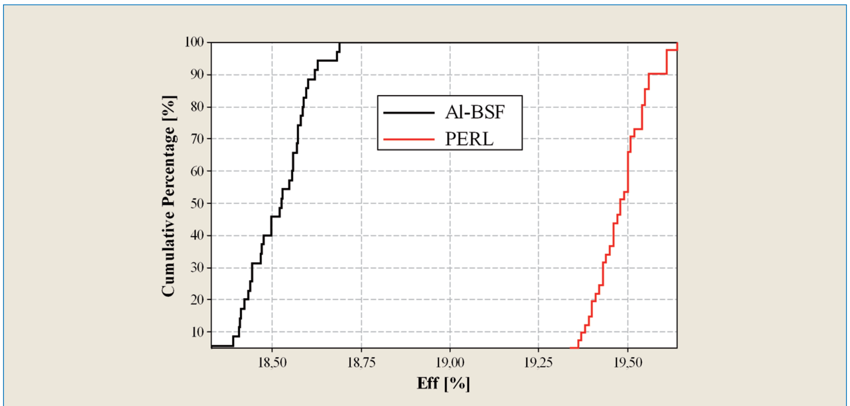

Figure 7. Cumulative percentage distribution of efficiency for full Al-BSF and optimized PERL-type Si solar cells.

> "Photovoltech's industrial PERL process was shown to be capable of achieving an average efficiency of 19.5% and a top efficiency of 19.7%."

Conclusions

This paper has reviewed some of the optimizations done at Photovoltech that aim to accelerate the industrialization of PERL-type monocrystalline silicon solar cells. The integration of these optimizations in Photovoltech's reference PERL process flow has been tested in

	J_{sc} [mA/cm²]	V_{oc} [mV]	*FF* [%]	Eff [%]
PERL	38.35	648	78.5	19.48
Al-BSF	37.30	633	78.7	18.52

Table 1. Average electrical parameters for optimized PERL-type and full Al-BSF Si solar cells, measured at standard test conditions (AM 1.5G, 1000W/m², 25°C).

large-batch experiments and benchmarked with the reference full Al-BSF process. Photovoltech's industrial PERL process was shown to be capable of achieving an average efficiency of 19.5% and a top efficiency of 19.7%. Moreover, the spread of the cumulative distributions of PERL and BSF solar cells was similar, demonstrating good control of the PERL-specific process steps – a very important advantage in large-scale manufacturing.

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