The road to industrializing PERC solar cells

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ABSTRACT

The passivated emitter and rear contact (PERC) cell design is gaining acceptance in solar cell manufacturing because of its potential for high efficiency with p-type wafers and its easy integration into existing production lines. In terms of PERC mass production, an effective and reliable AlO_x deposition tool is the most important aspect that needs to be considered. Light-induced degradation (LID) is a cell efficiency bottleneck because of bulk recombination, even if the silicon surface is well passivated. This paper examines the combination of cell efficiency, AlO_x tool choice and LID regeneration as a route to industrializing PERC technology.

Introduction

With the PERC design, a ~0.6–1.0% gain in cell efficiency is achievable for p-type mono solar cells, while ~0.5–0.8% is possible for multi cells, which is very attractive to the industry. Batch cell efficiencies of 19.0% for multi PERC and 20.70% for mono PERC solar cells have been reported in a pilot run.

Atomic layer deposition (ALD) and inline plasma-enhanced chemical vapour deposition (PECVD) AlO_x are currently the only two choices on the market for AlO_x deposition. A comparison of these two tools, with regard to passivation effect and cell efficiency, shows little difference between them, although ALD seems slightly better. On the other hand, high-deposition rate PECVD AlO_x has the advantage of higher throughput and uptime, which is more appealing to customers.

The boron–oxygen (B–O) complex is the origin of light-induced degradation (LID) in solar cells. Cell efficiency is limited by the bulk recombination, even if the silicon surface is well passivated; in other words, the extra efficiency gained by the excellent surface passivation of PERC cells will be reduced by bulk material LID. In this paper the results of an LID-regeneration evaluation test by thermal and light illumination are reported. Tests at the cell level have revealed that, after LID regeneration, the relative degradation is around 2.0% for mono PERC and 1.1% for multi PERC, which are acceptable results.

Purpose of the work

PV technologies are under challenge to reduce the cost of solar cells and increase their efficiency. Most state-of-the-art industrial solar cells use p-type Si as the base material; featuring an aluminium back-surface field (Al-BSF) on the rear surface, these cells suffer from rear-surface recombination and a low internal reflectance. Additionally, the bowing induced as a result of the thinness of the wafers limits the amount by which the silicon material used at the wafer level can be reduced. In order to achieve a higher conversion efficiency, however, the quality of the rear-surface passivation and reflectance needs to be higher than what Al-BSF can provide.

> “PERC structures allow an increase in efficiency and at the same time a decrease in wafer thickness.”

The application of passivated emitter and rear contact (PERC) structures (see Fig. 1) to industrial solar cell production, therefore, would allow an increase in efficiency and at the same time a decrease in wafer thickness. In a PERC cell, the full-area aluminium is replaced by a dielectric film covered with an aluminium film. The dielectric layer is then locally opened, to provide contact between the Al and the Si wafer.

A wide range of materials can be used for the rear-surface dielectric [1] (SiO_2 [2], a-Si [3], a-SiC_x [4]). Recently, AlO_x layers deposited by lab-type plasma-enhanced chemical vapour deposition (PECVD) [5] and high-deposition rate PECVD [6] have demonstrated that excellent surface passivation is provided with p-type surfaces too, eliminating the throughput restrictions of conventional atomic layer deposition (ALD) systems. Alternatively, very thin ALD Al_2O_3 capped by PECVD SiN_x or PECVD SiO_x, which also show very good surface passivation quality [7], could be used for industrial production.

A PERC process for mono and multi silicon material will be presented, cell efficiency evaluated, and the passivation effect and cell efficiency of ALD and inline PECVD AlO_x tools compared in order to determine any differences in passivation. An LID regeneration evaluation test by thermal and light illumination will also be discussed.

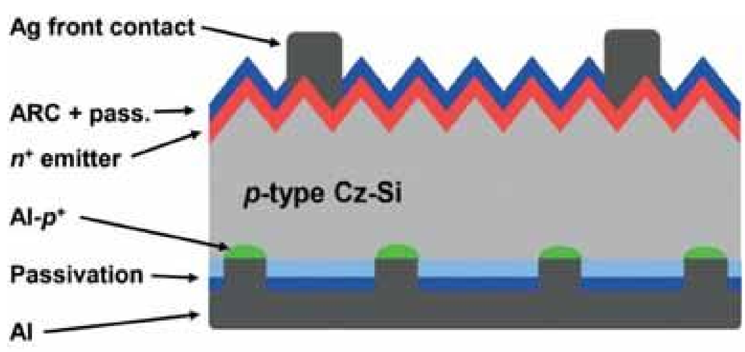

Figure 1. Schematic of a PERC solar cell.

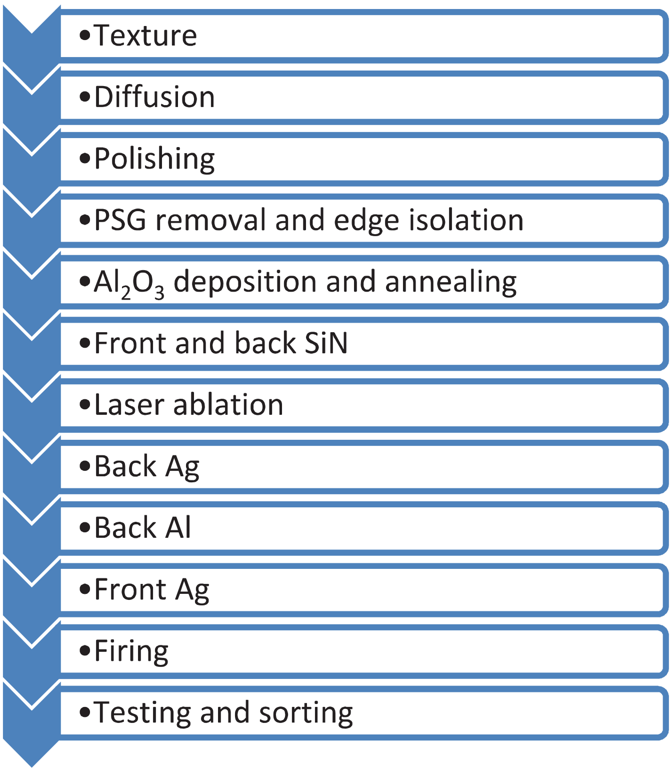

Figure 2. PERC process flow.

Approach

Cell efficiencies of mono and multi PERC solar cells

For the fabrication of the PERC solar cells, several thousand mono and multi wafers were processed in the pilot line. Fig. 2 shows the process flow sequence, more details of which can be found in previous publications [1,6].

The as-cut wafers passed through a conventional acid solution to create the textured surface. One step of single-side $POCl_3$ diffusion was then used to form a lightly doped homogeneous emitter. The rear surface was polished for the preparation of the PERC structure, followed by phosphor-silicate glass (PSG) removal. A thin layer of ALD Al_2O_3 was deposited on the rear surface, and PECVD SiN_x was deposited on both the front and the rear surfaces. After deposition, a green laser (532nm) was used for the local opening on the rear dielectric stack layers. Finally, screen printing and co-firing, as the metallization steps, were carried out to form the emitter contact and BSF field.

Cell efficiency reached around 19% with the PERC approach for multi silicon wafers, while the reference group reached 18.3% with traditional processing; an efficiency gain of ~0.7%

Lot	V_{oc} [mV]	I_{sc} [A]	FF [%]	R_s [mΩ]	R_{sh} [Ω]	Eff [%]	I_{rev1} [A]
Reference	634.5	8.761	80.11	1.7	123.69	18.30	0.18
PERC-1	642.4	9.131	78.9	2.34	72.19	19.02	0.21
PERC-2	642.4	9.122	78.87	2.43	80.7	18.99	0.213
PERC-3	644.3	9.129	78.78	2.49	106.07	19.04	0.165

Table 1. PERC cell efficiency for multi wafers.

Lot	V_{oc} [mV]	I_{sc} [A]	FF [%]	R_s [mΩ]	R_{sh} [Ω]	Eff [%]	I_{rev1} [A]
Reference	639.8	9.26	80.47	1.59	171.9	19.63	0.10
PERC-1	659.4	9.603	78.72	2.66	141.9	20.53	0.18
PERC-2	659.7	9.594	78.61	2.74	141	20.49	0.19
PERC-3	659.9	9.610	79.31	2.33	164.2	20.71	0.12

Table 2. PERC cell efficiency for mono wafers.

was therefore achieved at the cell level (see Table 1). For mono cells, the efficiency reached around 20.7% with the PERC approach, while the reference group yielded 19.6%; this equated to an efficiency gain of ~1.1% at the cell level (see Table 2).

AlO_x tool evaluation

For PERC mass production, an effective and reliable AlO_x deposition tool is the most important factor that needs to be considered. ALD and inline PECVD AlO_x tools are currently the only two choices available on the market; in this section their passivation behaviours and PERC efficiencies will be compared.

First of all, a non-contact capacitance–voltage (CV) measurement was performed in order to extract the total fixed charge density (Q_{fix}) and the interface defect density (D_{it}). The results are given in Table 3; these data demonstrate a good field passivation in both cases.

To examine the Al_2O_3 passivation further, the effective minority-carrier lifetime was characterized using the Sinton QSSPC method. With the measured lifetime data, the effective surface recombination velocity (SRV) S_{eff} is given by:

$$S_{eff} = \frac{W}{2}\left(\frac{1}{\tau_{eff}} - \frac{1}{\tau_{bulk,intrinsic}}\right) \quad (1)$$

where W is the wafer thickness, τ_{eff} is the effective lifetime and $\tau_{bulk,intrinsic}$ is the bulk lifetime. The effective SRV S_{eff} was calculated using Equation 1 for the polished wafers passivated by ALD AlO_x/SiN_x and by PECVD AlO_x/SiN_x. After the firing process, the calculated S_{eff} was 12cm/s for ALD AlO_x/SiN_x and 20cm/s for PECVD AlO_x/SiN_x (at a carrier injection level of $\Delta n = 1\times10^{15}cm^{-3}$).

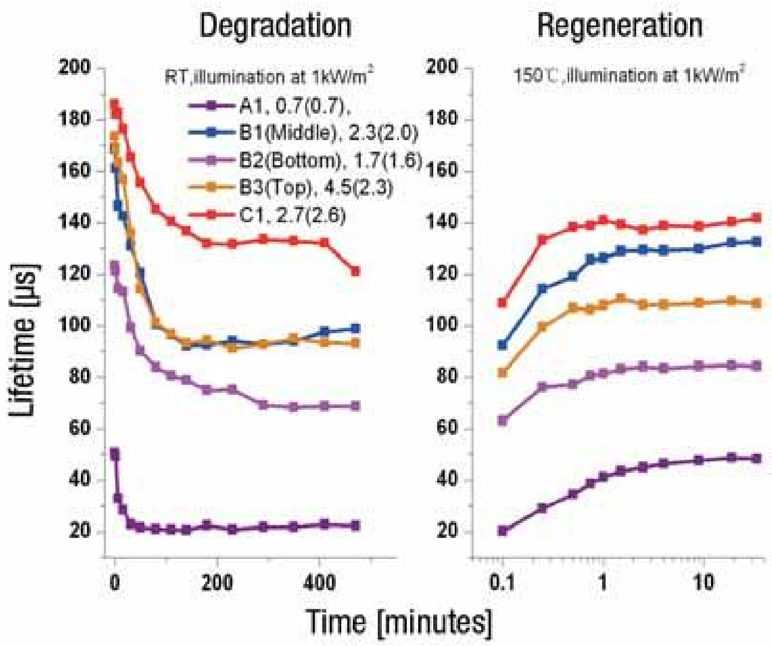

Figure 3. LID and regeneration lifetime–time curve for various resistivities (A, B, C refers to different ingots). The data in brackets are the resistivities measured after the oxygen thermal donor dissolved.

Passivation	Q_{fix} [cm^{-2}]	D_{it} [cm^{-2}ev^{-1}]
PECVD AlO_x/SiN_x	-3.61×10^{12}	1.13×10^{12}
ALD AlO_x/SiN_x	-3.95×10^{12}	9.44×10^{11}

Table 3. Total fixed charge (Q_{fix}) and interface defect density (D_{it}) for PECVD and ALD AlO_x/SiN_x stack layers.

Lot	V_{oc} [mV]	I_{sc} [A]	FF [%]	R_s [mΩ]	R_{sh} [Ω]	Eff [%]	I_{rev1} [A]
ALD	659.9	9.588	79.0	2.15	150.5	20.59	0.14
PECVD	659.2	9.575	79.0	2.14	147.5	20.53	0.14

Table 4. PERC cell efficiency for mono wafers using ALD and inline PECVD AlO_x tools.

To verify the passivation effect even further, two groups of mono PERC cells (manufactured following the process flow sequence in Fig. 2) were used to demonstrate the differences in cell efficiency; the details are given in Table 4. Only very slight differences in passivation effect and cell efficiency were found between the ALD and PECVD passivation methods. The high-deposition rate PECVD AlO_x, however, has the advantage of a higher throughput and uptime, which is more appealing to customers.

Light-induced degradation and regeneration

As mentioned earlier, the source of light-induced degradation (LID) in solar cells is the B–O complex. Cell efficiency is limited by bulk recombination, even if the silicon surface is well passivated; in other words, the extra efficiency gained by excellent surface passivation of a PERC cell will be reduced by bulk material LID.

The total light-generated B–O pairs are directly proportional to the boron concentration and to the square of the oxygen concentration. The generation rate, however, is only related to the boron concentration, which is the reason why much of the efficiency gain is lost in the case of mono silicon material, thus preventing it from entering into mass production.

LID can be reduced by regenerating the silicon bulk lifetime through directly passivating the generated B-O complex, but only if the H-rich sample is simultaneously annealed at an elevated temperature [8–10]. Hydrogen is believed to play a key role in the B–O deactivation process. The regeneration rate is also limited by high boron or oxygen concentrations.

Fig. 3 shows the lifetime regeneration data for different zones in an ingot, taken from a previous study [11]; from this it can be inferred that a portion of the lifetime recovery is achieved by light illumination at an elevated temperature. To allow further verification, more mono and multi PERC cells were fabricated and tested initially using an *I*–*V* tester. After the light regeneration and subsequent degradation tests under 1 sun illumination for 72 hours, the relative degradation data shown in Table 5 were obtained.

> "LID in the cell could be comfortably less than 3% rel. for mono PERC cells, and less than 2% rel. for multi PERC."

Cell	State	Efficiency	Relative degradation
Multi	Before	18.98%	1.07%
	After	18.78%	
Mono	Before	20.59%	2.00%
	After	20.18%	

Table 5. PERC cell efficiency before light illumination and after LID regeneration and light illumination.

Table 5 indicates that the LID in the cell could be comfortably less than 3% rel. for mono PERC cells, and less than 2% rel. for multi PERC. The implementation of the approach could therefore be industrially feasible, provided the degradation can be controlled to within a reasonable range, say ~2–3%, at the module level.

Conclusions

A PERC approach for both mono and multi silicon material has been presented, with efficiency gains of 1.1% and 0.7% being demonstrated at the mono and multi cell levels respectively. ALD and inline PECVD AlO_x show only very slight differences in passivation effect and cell efficiency; however, high-deposition rate PECVD AlO_x is more appealing to customers because of its higher throughput and uptime. An LID regeneration process can help to address LID issues, by reducing the loss in efficiency to less than 3% rel. for mono PERC cells, and to less than 2% rel. in the case of multi PERC. The approaches outlined above constitute one direction that can be taken towards the industrialization of PERC technology.

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