HIGH-EFFICIENCY *P*-TYPE PERC SOLAR CELLS APPLYING PECVD ALO$_X$ LAYERS

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ABSTRACT: Ultrathin (7 nm) ALD Al$_2$O$_3$ layers and high-deposition-rate PECVD AlO$_x$ layers have the potential to become the rear surface passivation for the next generation of *p*-type silicon industrial solar cells. These passivation layers have been applied on laboratory-scale passivated-emitter-and-rear solar cells. Efficiencies higher than 21 % have been achieved. The illuminated current-voltage measurement and the external quantum efficiency confirm that the rear surfaces are providing a high passivation quality and internal reflectance. Based on this experiment we can conclude that these two technologies have probably very similar potential when applied on solar cells. Consequently it will probably be more the deposition system than the deposition technique that will be the main criteria for the choice of one of the technologies. Finaly PECVD and ALD deposition systems are compared in important criteria for industrial solar cell production.
Keywords: ALD, PECVD, aluminum oxide.

1 INTRODUCTION

Photovoltaic (PV) technologies are challenged to reduce solar cells' cost and increase their efficiency. Most of state-of-the-art industrial solar cells are using *p*-type Si as the base material. Featuring an aluminum back-surface field (Al-BSF) on the rear surface, they suffer from rear-surface recombinations and a low internal reflectance. Additionally, the bowing induced for thin wafers limits the reduction of silicon material used.

Lab-type passivated-rear solar cells applying laser-fired rear contacts allow high conversion efficiencies (up to ~22% [3] on *p*-Si). In order to achieve this range of conversion efficiency the quality of the rear-surface passivation and reflectance needs to be higher than what Al-BSF can provide. Therefore the application of these structures to industrial solar cell production would allow an increase of the efficiency while decreasing the wafer thickness.

A wide range of materials can be applied for rear-surface passivation [5] (SiO$_2$ [6], a-Si [11-13], a-SiN$_x$ [14], a-SiC$_x$ [15]). Al$_2$O$_3$ layers deposited by atomic-layer deposition (ALD) have shown that they can provide low surface recombination velocities on lowly-doped and highly-doped *p*-type Si surfaces [16, 17]. These layers have been applied to the rear surface of laboratory *p*-type rear-passivated solar cells leading to conversion efficiency values up to 20.6 % [18]. For the solar cells presented in Ref. [18], the rear-surface passivation and internal reflection of thermally grown SiO$_2$ and ALD Al$_2$O$_3$ are similar. ALD Al$_2$O$_3$ is therefore well suited for rear-passivated *p*-type solar cells application. Recently ultrathin ALD Al$_2$O$_3$ passivation layers [8] and high-deposition-rate plasma-enhanced chemical–vapor-deposited (PECVD) AlO$_x$ layers [1] have shown to provide excellent surface passivation on *p*-type surfaces. These layers can be used to circumvent aluminum oxide limits to industrial applications.

In this paper we use *p*-type inverted-pyramid passivated-emitter-and-rear solar cells (IP-PERC) produced in laboratory as test structures to compare ultrathin Al$_2$O$_3$ layers and PECVD AlO$_x$ passivation layers. The layers have been applied to the rear surface and compared to a reference layer, thermally grown SiO$_2$ [2]. This high efficiency structure is well suited to evaluate the limit of efficiency allowed by the rear-passivation layers up to ~22%.

2 EXPERIMENT

As starting material we use <100>-oriented 0.5 Ω.cm float-zone (FZ) *p*-type c-Si wafers with a thickness of 250 μm. In order to define the inverted pyramid pattern on the front surface, an oxide mask is grown and structured by photolithography. The pyramids are then etched in KOH. After growing a new oxide mask, 2×2 cm^2 windows are opened, and the emitter is formed by phosphorus diffusion. After the removal of the phosphorus glass and the remaining SiO$_2$, a dry oxidation at 1100°C is carried out, leading to a 105-nm-thick SiO$_2$ layer. The resulting final sheet resistance of the front-side emitter is 120 Ω/sq. For the solar cells passivated by aluminum oxide, the rear-side SiO$_2$ layer is removed before the rear-side aluminum oxide deposition process. A total of five groups with different rear-side passivation layer systems were processed (the stacks are written in the order of the deposition process):

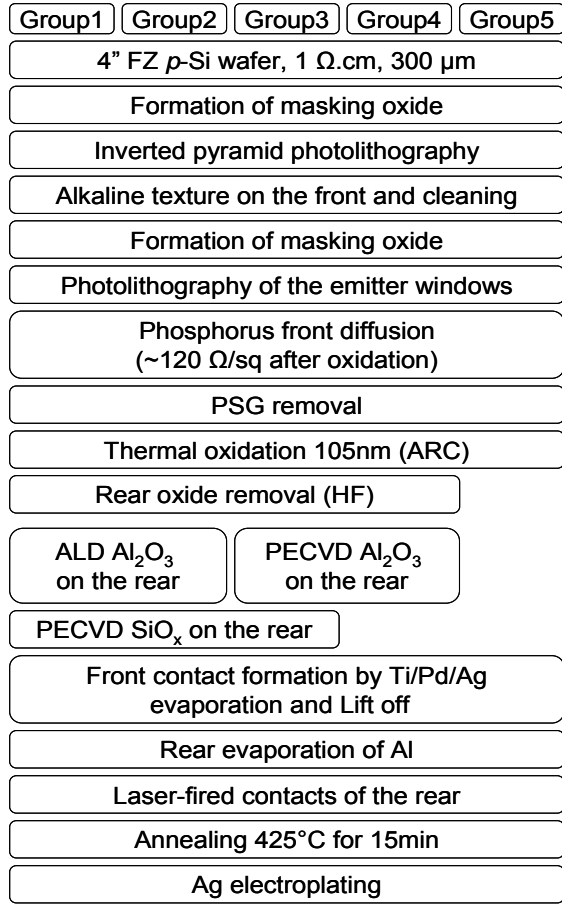Group 1: ultrathin (7 nm) ALD Al$_2$O$_3$ and 90 nm PECVD SiO$_x$;

Group 2: 20 nm ALD Al$_2$O$_3$ and 80 nm PECVD SiO$_x$;

Group 3: 30 nm PECVD AlO$_x$ and 70 nm PECVD SiO$_x$;

Group 4: 100 nm PECVD AlO$_x$;

Group 5: reference group, SiO$_2$ 105 nm.

To realize the front contacts, the SiO$_2$ layer was opened using photolithography, a Ti/Pd/Ag stack was evaporated (e-gun) and structured by a lift-off process. At the rear-side, aluminum was evaporated on top of the dielectric passivation. The local contacts were performed using the lased-fired contact (LFC) process. Then, the cells were submitted to a final forming gas annealing at 425°C for 15 min. Finally, the front contacts were

Group1 | Group2 | Group3 | Group4 | Group5

- 4" FZ *p*-Si wafer, 1 Ω.cm, 300 µm
- Formation of masking oxide
- Inverted pyramid photolithography
- Alkaline texture on the front and cleaning
- Formation of masking oxide
- Photolithography of the emitter windows
- Phosphorus front diffusion (~120 Ω/sq after oxidation)
- PSG removal
- Thermal oxidation 105nm (ARC)
- Rear oxide removal (HF)
- ALD Al_2O_3 on the rear | PECVD Al_2O_3 on the rear
- PECVD SiO_x on the rear
- Front contact formation by Ti/Pd/Ag evaporation and Lift off
- Rear evaporation of Al
- Laser-fired contacts of the rear
- Annealing 425°C for 15min
- Ag electroplating

Figure 1: Process flow used for the fabrication of high-efficiency solar cells.

Table I: Solar cell characteristics resulating of illuminated current voltage measurements at one sun intensity. The high-efficiency solar cells (4 cm²) are passivated with PECVD aluminum oxide, ALD aluminum oxide and thermally grown silicon dioxide.

Rear surface passivation	V_{oc} [mV]	J_{sc} [mA cm^{-2}]	FF [%]	η [%]
Thin ALD Al_2O_3 + SiO_x	**681**	**39.3**	**79.6**	**21.3**
Mean / Std dev. [a] 7 cells	677 / 2	39.6 / 0.4	78.8 / 1.6	21.1 / 0.5
ALD Al_2O_3 + SiO_x	**676**	**40.2**	**78.5**	**21.2**
Mean / Std dev. 7 cells	674 / 2	40.0 / 0.2	72.9 / 4.2	19.7 / 1.1
PECVD AlO_x + SiO_x	**678**	**39.7**	**79.4**	**21.3**
Mean / Std dev. 7 cells	677 / 1	39.5 / 0.1	78.7 / 1.1	21.0 / 0.3
PECVD AlO_x	**684**	**39.4**	**79.8**	**21.5**
Mean / Std dev. 7 cells	680 / 1	39.9 / 0.2	77.8 / 1.1	21.1 / 0.4
Thermal SiO_2	**685**	**39.2**	**79.8**	**21.4**
Mean / Std dev. 7 cells	683 / 1	39.7 / 0.1	78.7 / 1.3	21.3 / 0.4
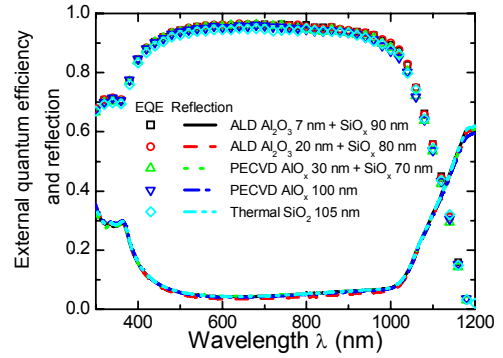
Figure 2: External quantum efficiency and reflection as a function of the wavelength for high-efficiency solar cells passivated with aluminum oxide and with silicon dioxide layers [2].

thickened using light-induced plating of Ag. Fig. 1 shows the process flow followed for this batch.

A wet chemical cleaning consisting of hot HNO_3 for 10 min followed by HF for 1 min is carried out before the aluminum oxide deposition. The deposition of ALD Al_2O_3 is performed in a single-wafer plasma-assisted atomic-layer-deposition (PA-ALD) system (OpAL; Oxford). The deposition of PECVD AlO_x is performed in an inline system (SiNA; Roth&Rau). The minimal static deposition rate obtained is more than one order of magnitude higher as standard ALD [1]. Additionally as this system in already in use in industrial production, PECVD AlO_x processes can be quickly spread out. The deposition of SiO_x is performed in the same PECVD system. After deposition of the passivation layers a forming gas annealing at 450°C for 25 min and a measurement of the lifetime are performed in order to control the passivation quality before finishing the solar cell process.

3 RESULTS

3.1 Illuminated current-voltage measurements

Table I presents the results of the current-voltage measurements of the cells of each group. The measurement is performed under illumination of one sun intensity. High conversion efficiencies of up to 21.3 % have been obtained using ultrathin ALD Al_2O_3 rear-surface passivation. Additionally 21.5 % has been obtained using high-deposition-rate PECVD AlO_x at the rear surface. Similar efficiencies have been obtained using SiO_2 for the rear-surface passivation (21.4%). A few cells from the second group suffer from a low fill factor (FF), therefore the average value of the efficiencies of this group is not significant. However the best cell of this group has an efficiency value of 21.2 %. High open-circuit voltages (V_{oc}) around 680 mV have been obtained in each group, showing the high effective carrier lifetime in the solar cell and therefore the high rear-surface passivation quality. High short-circuit current densities (j_{sc}) around 40 mA/cm² have been also obtained in each group showing the highly efficient light trapping and internal reflectance.

3.2 External quantum efficiency and reflection

The external quantum efficiencies (EQE) and the reflection of the solar cells have been measured at 0.3 suns bias light intensity for wavelengths from 250 nm to 1200 nm, the results are shown in Figure 2. The high EQE in the high wavelength range (900 nm to 1200 nm) for all groups shows the good quality of the rear surface passivation. The high light reflection in the high wavelength range testifies that internal rear surface reflectance is high. Therefore the aluminum oxide passivation layers of this work, independent of the deposition technique, are comparable to silicon oxide passivation when applied on *p*-type solar cells.

Table II: Comparison PECVD, PA-ALD, thermal ALD and sputtering aluminum oxide layers characteristics. The references for the PECVD Al_2O_3 are ref. [1], [4]; for the PA-ALD ref. [7-9]; for the thermal ALD ref. [8],[20] are used and for sputtering ref. [10],[20],[21].

Deposition technique	PECVD	ultrathin PA-ALD	Thermal-ALD	Sputtering
Passivation[a] (S [cm.s^{-1}])	< 10	< 10	< 10	< 20
Negative charges [cm^{-2}]	2-5 10^{12}	1 10^{13}	2-3 10^{12}	~3 10^{12}
Firing stable[a] (S [cm s^{-1}])	~ 10	< 20	< 20	< 20
Highest efficiencies so far (p-type)	21.5 %	21.3 %	20.7 %	20.1 %
Minimal thickness d_{min} [nm]	10-15	5-7	10-15	< 20

[a] for p-Si ranging 0.5-3 Ω.cm.

4 DISCUSSION

4.1 Aluminum oxide layers for p-type solar cells

As proven in this paper ultrathin ALD and high-deposition-rate PECVD aluminum oxide allow efficiencies higher than 21 % when they are applied to the rear of p-type solar cells. It is expected that the potential of these layers is also comparable for application on industrial solar cells. Other techniques can be applied for the deposition of aluminum oxide. Table II shows a comparison of aluminum oxide layers obtained by a wider range of deposition techniques (PECVD, PA-ALD, thermal ALD and sputtering).

Despite the differences in the aluminum oxide layer characteristics reported (see table II), all these layers seem compatible with the application on p-type industrial solar cells with probably similar potential. Therefore the choice of one aluminum oxide deposition technology for solar-cell mass production should be based on the deposition system itself more than the deposition technique.

4.2 Comparison of the aluminum oxide deposition systems

Three types of deposition systems can potentially reach high throughput and therefore at compatible solar cells mass production:

- Inline PECVD,
- Inline sputtering,
- Ultrafast ALD [19].

Inline PECVD and sputtering offer the advantages to be already in use in the solar cell industry and silicon nitride can be deposited in the same system. Inline PECVD and ultrafast ALD aluminum oxide offer a comfortably high deposition rate. The cleaning of the chamber is a disadvantage of PECVD deposition. Inline sputtering has the advantage that it does not need expensive TMAl, however it at the moment shows a relatively low deposition rate[10]. Ultrafast ALD presents the advantages that it does not need any vacuum and that it produces very homogeneous pinhole-free layers. However it is still in the prototype phase and conclusions on this technology are premature.

CONCLUSION

Efficiencies above 21 % have been proven using ultrathin PA-ALD Al_2O_3 and PECVD AlO_x layers for the rear-surface passivation of p-type silicon solar cells. This shows that PA-ALD Al_2O_3 and PECVD AlO_x layers have similar potentials for industrial solar cell application. Therefore the deposition *system* and its compatibility with the cell production line is expected to be an important criterion for the choice of a deposition technology for the industrial application of aluminum oxide.

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