

P-TYPE CZ-SI PERC-TYPE SOLAR CELLS APPLYING PECVD ALUMINUM OXIDE REAR SURFACE PASSIVATION

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ABSTRACT: A high-deposition-rate plasma-enhanced chemical-vapor-deposition (PECVD) technique has been used to deposit high-quality aluminum oxide (AlO_x) layers for silicon surface passivation. Effective-carrier-lifetime values over 2 ms have been measured on *p*-type $1 \Omega\cdot\text{cm}$ float-zone silicon wafers symmetrically deposited with PECVD AlO_x . This passivation layer has been applied on large-area industrial-type solar cells where the contacts have been obtained using screen printing, cofiring and laser-fired contacts (LFC). A higher open-circuit voltage and a higher short-circuit current density were demonstrated for the rear-passivated solar cells compared to state-of-the-art aluminum-back-surface-field (Al-BSF) solar cells.

Keywords: Industrial solar cell, PECVD, aluminum oxide.

1 INTRODUCTION

In the main share of crystalline silicon solar cells industrially produced today, the rear surface is fully covered by an aluminum-back-surface field (Al-BSF). The Al-BSF is formed by a well-established process; it can also provide a sufficient surface passivation to obtain relatively high efficiencies of 19.1 % [2] industrially-produced *p*-type-silicon solar cells. However, Al-BSF provides a relatively poor internal reflectance and induces a high mechanical stress. Therefore it is not well suited for thin ($< 180 \mu\text{m}$) solar cells even though low-bow Al screen-printing pastes are commercially available.

The rear-passivated solar-cell structures introduce a layer that enhances the passivation and the reflection at the rear surface, and limits the mechanical stress [3]. This structure is therefore well suited for thin solar cell manufacturing while the solar cell performance is enhanced by rear passivation and the high internal reflection.

In the last years a particular attention has been given to negatively charged dielectrics for silicon-surface passivation and especially to aluminum oxide [4-6]. Recently, ultrathin Al_2O_3 layers deposited by atomic layer deposition (ALD) and AlO_x deposited by high-deposition-rate PECVD have shown efficiencies higher than 21 % [7] when applied on laboratory scale *p*-type rear-passivated solar cells. Therefore both deposition techniques have similar potential for the application on industrial solar cell.

Typical deposition rates of PECVD systems are higher than lab-scale ALD deposition systems. Recently developed ultrafast ALD deposition systems offer the opportunity to obtain ALD processes with the throughput required by solar cell mass production. The suitability of high-deposition-rate PECVD and ALD to solar cell production has been investigated and is presented at this conference [7, 8].

In this study aluminum oxide deposited by PECVD is applied to large-area silicon solar cells. The solar cells have been mainly produced in the pilot line PVTEC of Fraunhofer ISE [9]. All the equipments used for the

fabrication are state-of-the-art tools dedicated to solar cell mass production.

2 EXPERIMENT

2.1 PECVD aluminum oxide deposition

The aluminum oxide layers used for this study have been deposited in an inline PECVD system presented in Figure 1 (SiNA, Roth and Rau). Such deposition systems are typically used for the deposition of anti-reflection coating (ARC) silicon nitride in industrial solar cell production. The throughput enabled by such tools is ranging 4000 wafers / hour.

A high dynamic deposition rate of more than 25 nm / min has been demonstrated maintaining an excellent surface passivation quality [6]. Figure 2 shows the effective carrier lifetime obtained on a silicon wafers ($<100>$ -oriented float-zone silicon, $1 \Omega\cdot\text{cm}$, 250 μm thick) symmetrically deposited with 50 nm PECVD AlO_x layer and annealed at a temperature of 400°C. The lifetime peaks at a value higher than 2 ms showing a maximum surface recombination velocity of about 6 cm s^{-1} .

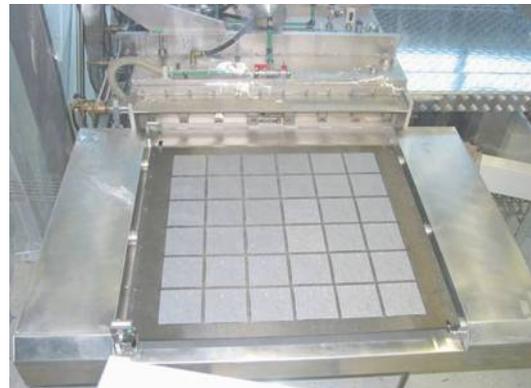


Figure 1: Image of the wafer tray of the industrial PECVD inline system used in this study (Roth&Rau SiINA).

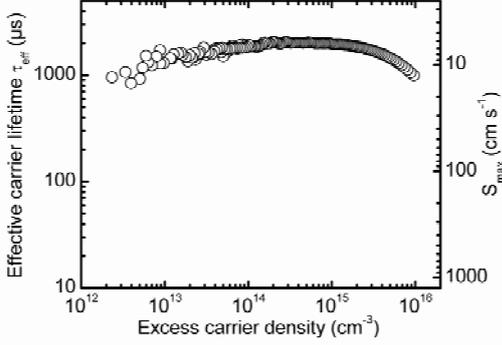


Figure 2: Effective carrier lifetime and the corresponding S_{\max} as a function of the excess carrier density of a sample symmetrically deposited with 50 nm PECVD AlO_x as measured after forming gas anneal. The substrate was (100) float zone (FZ) Si p -type 1 Ω cm and 250 μm thick.

2.2 Firing stability of PECVD aluminum oxide

The firing stability of aluminum oxide has been demonstrated for ALD layers [10, 11]. In these cases the firing can replace the forming gas anneal and activate the aluminum oxide passivation. In contradiction with silicon dioxide no extra temperature step is needed after the firing.

PECVD aluminum oxide firing stability is studied in Ref. [12]. In the same study thin aluminum oxide layer (< 30 nm) have demonstrated to provide a low surface recombination velocity on p -type silicon. PECVD silicon nitride or silicon dioxide layers can be used as a capping. However they are not needed to obtain high-quality passivation after firing.

2.3 Internal reflection and capping layer

For economic reason the use of thin aluminum oxide layers is interesting considering the price of TMAI. In this case silicon nitride and silicon dioxide capping layers can be used in order to enhance the rear-side internal reflection. In Green's textbook [13] a graph of the rear surface internal reflectance as a function of silicon dioxide thickness can be found. An important increase of the reflectance can be observed between 10 nm the 100 nm silicon dioxide layer thickness. As a first approximation we can consider that aluminum oxide stacked with silicon dioxide or silicon nitride behaves in a similar way (replacing the SiO_2 thickness by an equivalent optical thickness). In this case a total stack thickness of around 100 nm will have a higher internal reflectance compared to a stack of around 15 nm. For the solar cells fabricated in this study a total stack (aluminum oxide with capping) thickness of at least 100 nm has been used.

2.4 Solar cell process

Czochralski (Cz) grown p -type silicon 2 Ω .cm wafers were chosen as the starting material. The wafer shape is 125 mm \times 125 mm pseudo square with a thickness of \sim 170 μm . The first process consists of removing the saw damage and at the same time texturing the silicon surface in a KOH/isopropanol solution. The rear surface of the wafer is then polished in a silicon etching solution

(HNO_3 / CH_3COOH / HF / H_2O). A 65 Ω/sq emitter is diffused on both sides of the silicon wafer. The emitter on the rear surface is removed in a second silicon etching solution. An HF dip is used to clean the wafer surface before the AlO_x deposition on the rear surface. The aluminum oxide deposition was performed in the high-throughput inline PECVD system described in section 2.1. The front antireflection coating and the rear-side capping layer were deposited in the same machine type as the aluminum oxide layers. In a real industrial application the three PECVD layers can be deposited in the same system without breaking the vacuum between the different processes. The front and the rear contacts were obtained by screen printing and cofiring in an inline belt furnace. Laser-fired contacts were performed on the rear screen-printed aluminum in order to contact the base locally through the dielectric [14]. A light-induced plating of silver was performed at the end of the process in order to thicken the front contacts and decrease the series resistance. A group of solar cells received every processes except the deposition of the passivation stack on the rear surface and the laser-fired contacting of the rear. This group corresponds to the reference state-of-the-art industrial solar cell featuring an aluminum-back-surface field (Al-BSF).

3 RESULTS AND DISCUSSIONS

3.1 Illuminated current-voltage measurement

The current-voltage characteristics of the solar cells were measured in an inline solar cell tester before degradation. The parameters of the solar cells under one-sun intensity are reported in Table I. A slight increase of the open-circuit voltage (V_{oc}) and an important increase of the short-circuit current (I_{sc}) are observed for the solar cells passivated with PECVD aluminum oxide compared to the Al-BSF reference solar cells. However the fill factor of the AlO_x -passivated solar cells is lower than the Al-BSF solar cells due to a higher series resistance.

The efficiency of rear-passivated solar cells presented here does not show the real efficiency potential of the PECVD AlO_x layers used. In fact, the low fill factor due to a high series resistance is very probably independent from the AlO_x passivation. The contacts, that have been applied, should lead to a fill factor of 78 %. This would imply an efficiency increase of 4-5 % relative

3.2 Internal quantum efficiency and reflection

The internal quantum efficiency was measured for one solar cell of each group. The measurement was performed on the complete solar cell area, under 0.3 suns bias light. We observed an important increase of the IQE

Table I: Characteristics under one-sun illumination of the industrial solar cells (CZ-Si, 125 mm pseudo square, \sim 170 μm thick)

Rear surface passivation	V_{oc} [mV]	J_{sc} [mA cm $^{-2}$]	FF [%]	η [%]
PECVD $\text{AlO}_x/\text{SiN}_x$ best	627	38.7	73.9	18.0
Mean / Std dev. 20 cells	620 / 11	37.7 / 1.5	73.5 / 1.1	17.2 / 1.1
Al BSF best cell	619	36.9	77.2	17.7
Mean / Std dev. 20 cells	614 / 15	36.1 / 2.3	75.8 / 1.5	16.8 / 1.5

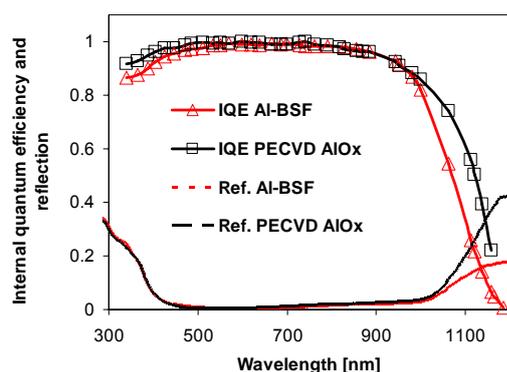


Figure 4: Spectral internal quantum efficiency and reflectance for solar cells passivated with Al-BSF and with PECVD AlO_x. The reflectance correspond to the reflectance of the solar cell excluding the front contact, this has been calculated based on the model of Fischer [1].

in the long wavelength regime that can be attributed to a higher internal reflection and a lower rear-surface recombination velocity for the solar cells featuring PECVD aluminum oxide on the rear.

The large reflection in the long-wavelength regime for the solar cell passivated with aluminum oxide is due to a large fraction of the light internally reflected at the rear surface.

4 CONCLUSION

Effective carrier lifetime values over 2 ms have been demonstrated on float-zone *p*-type 1 Ω.cm silicon wafers symmetrically coated with high-deposition-rate PECVD AlO_x. The industrial solar cells, applying PECVD aluminum oxide on the rear surface, have shown higher V_{oc} and higher I_{sc} than the Al-BSF reference solar cells. However, we observed only a small efficiency increase between the two solar cell types because of a relatively lower fill factor for the rear passivated solar cells.

A higher rear internal reflectance for the solar cell passivated with PECVD AlO_x is shown by the long wavelength escape.

5 ACKNOWLEDGEMENT

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