INDUSTRIAL DEPOSITION OF PECVD AlO$_x$ FOR REAR PASSIVATION OF PERC-TYPE mc-SI SOLAR CELLS

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ABSTRACT: Passivated and locally rear contacted solar cell concepts are currently leaping forward towards industrial realization. A promising candidate for rear passivation represents the deposition of aluminum oxide (AlO$_x$) by means of plasma enhanced chemical vapor deposition (PECVD) techniques. High deposition rates, high gas utilization and good achievable layer homogeneities attract considerable interest for an industrial use of these types of layer systems. The paper reports on current activities towards an industrial implementation of PECVD deposited AlO$_x$ layers for rear passivation of multicrystalline silicon (mc-Si) solar cells. On large area PERC type mc-Si solar cells, an increase in V$_{oc}$ of about 1.5 % relative and in j$_{sc}$ of about 2.5 % relative compared to standard Al-BSF reference cells could be demonstrated, demonstrating the optical and electrical quality gain at the wafers rear side.
Keywords: Industrial solar cell, PECVD, aluminum oxide.

1 INTRODUCTION

In today's market, crystalline silicon wafer technology dominates the industrial solar cell production. Common devices feature opposing electrodes that are situated at the front and rear surface of the wafer and subsequent front-to-rear interconnection is used for module assembly.

Locally rear-contacted solar cells with dielectric passivation (passivated emitter and rear cell (PERC) concept) for high efficiency solar cells were introduced more than 20 years ago by e.g. Swanson and Sinton [1, 2]. Within the past ten years substantial efforts and progress have been made to introduce this concept to industrial mass production. Compared to the dominating full-area aluminum back surface field (Al-BSF) approach, the differences in device features needed in order to successfully implement such a structure into an industrial process are quite substantial. One major aspect, which has to be addressed, is the cleaning and surface conditioning as well as the passivation of the solar cells rear side. In the past, several classes of dielectric passivation layers have been investigated resulting in surface recombination velocities below 10 cm/s on lowly doped silicon [3]. In PERC-like cell structures, in-situ or subsequent deposition of additional layers can improve internal reflectance, act as diffusion barrier for the rear metal or even improve the passivation quality of the layer by injecting interface defect-passivating hydrogen or enhancing the fixed charge density to favourable energy band conditions.

Dielectric passivation layers exhibiting a high number of fixed positive charges (e.g. hydrogenated layers of amorphous silicon nitride, oxide or carbide as well as siliconoxynitrides) on p-type PERC cells suffer from an inversion layer induced by these charges in combination with non-ideal junctions of the local contacts, therefore much attention has been drawn towards negatively charged layers like Al$_2$O$_3$. Excellent passivation results have been already obtained on either atomic layer deposition or plasma enhanced chemical vapour deposition (PECVD) systems [4]. The latter offers the advantage of having a large area, fast deposition process with large wafer throughput capability. The paper reports on current progress of PECVD AlO$_x$ passivation layers for industrial PERC tyle mc-Si solar cells.

2 EXPERIMENT

2.1 PECVD aluminum oxide deposition

The aluminum oxide layers used for this study have been deposited in an inline PECVD system shown in Figure 1 (SiNA platform from Roth and Rau). A mix of trimethylaluminum (TMA, Al(CH$_3$)$_3$), nitrous oxide (N$_2$O) and argon was used as reactant gas. The plasma is created by 2.45 GHz microwave (MW) pulses, which are introduced to the reaction chamber via linear antennas.

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

2.2 Solar cell process

Multicrystalline silicon (mc-Si) wafers (p-type, specific resistivity 1.5 Ω.cm, thickness 200 μm, area 125x125 mm²) have been used as starting material. The process sequence for the fabrication of the industrial PERC-type mc-Si solar cells is depicted in Figure 2. After grouping of the neighboring mc-Si wafer and laser marking, removing of the saw damage and at the same

time texturing of the silicon surface is accomplished in a HF-HNO$_3$ solution. POCl$_3$ diffusion process has been used in order to form a 65 Ω/sq emitter layer on both sides of the silicon wafer. The emitter on the rear surface is afterwards removed within an acidic single side etching step, prior to the phosphorus glass removal. Cleaning of the wafers before passivation is done in a subsequent NH$_4$OH/H$_2$O$_2$ and HCl/H$_2$O$_2$ treatment ending with a HF dip before the AlO$_x$ deposition on the rear surface.

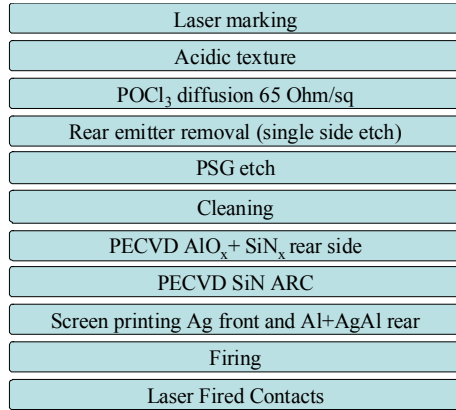| Laser marking |
|---|
| Acidic texture |
| POCl$_3$ diffusion 65 Ohm/sq |
| Rear emitter removal (single side etch) |
| PSG etch |
| Cleaning |
| PECVD AlO$_x$+ SiN$_x$ rear side |
| PECVD SiN ARC |
| Screen printing Ag front and Al+AgAl rear |
| Firing |
| Laser Fired Contacts |

Figure 2: Process sequence used for the fabrication of industrial PERC-type mc-Si solar cells.

The aluminum oxide deposition was performed in the high-throughput inline PECVD system described in section 2.1. The front antireflection coating layer and the rear side capping layer were deposited in the same machine type as the aluminum oxide layer. In a real industrial application the three PECVD layers can be deposited in the same system without breaking the vacuum between the different processes [5]. The front and the rear contacts are obtained by screen printing and cofiring in an inline belt furnace. Laser-fired contact are formed on the rear screen printed aluminum in order to contact the base locally through the dielectric stack layer [6]. In parallel to the rear passivated cells, one group of neighboring wafers has been processed without rear passivation, featuring a state-of-the-art screen-printed full-area aluminum back surface field for reference.

3 RESULTS AND DISCUSSION

3.1 Deposition rate

High dynamic deposition rate of more than 25 nm m / min have been demonstrated maintaining an excellent surface passivation quality [7]. The high reaction rate and a factor of about 4 higher utilization of the TMA precursor gas compared to e.g. Silane nearly fully compensates the higher chemical costs resulting in a very cost effective deposition with very low added value for the total cost of ownership within an industrial PERC-type process scenario (< 10 €ct/wafer for complete AlO$_x$ + SiN$_x$ stack layer deposition) [8]

3.2 Layer homogeneity and electrical quality

As TMA is a highly reactive chemical, localized deposition directly below the gas inlets has to be suppressed in order to ensure a homogeneous layer deposition. Detailed process analysis and optimisation

lead to AlO$_x$ layer homogeneities over the full deposition length plotted in Figure 3. The deposited layer thickness reaches a minimum value nearly in the middle of the deposition area, nevertheless, overall standard deviation from the average thickness can be kept below 10 % over the full deposition area.
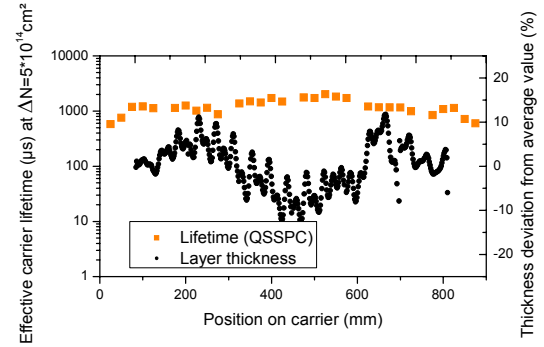

Figure 3: Layer homogeneity as well as measured effective carrier lifetimes over the full deposition width.

Shiny etched 1 Ω cm *p*-type silicon FZ-substrates with a thickness of 250 μm and a (100) crystal orientation are used for the investigation of the achievable effective carrier lifetime of AlO$_x$-passivated samples across the deposition width (results are also shown in Figure 3). The samples are used without any further cleaning in advance to the coating. τ_{eff} was measured using a quasi-steady state photo conductance (QSSPC) device on symmetrically both-side deposited samples. To fully exploit the lifetime potential, the samples underwent a thermal treatment under forming gas (ambience: 95 % N$_2$, 5 % H$_2$) at a temperature of 350 C. High carrier lifetimes between 500 and 1100 μs are achieved over the full deposition width, nearly independent of the achieved layer thickness. It can be concluded, that the layer thickness does not strongly influence the electrical quality of the passivation layer, but it has more influence on the firing stability [9].

3.3 Illuminated IV measurement

The current-voltage characteristic of the mc-Si solar cells has been measured in an inline solar cell tester in the as processed state. The parameter of the solar cell under one-sun intensity is reported in Table I.

Table I: Overview of IV results of the processed PERC type as well as reference Al-BSF mc-Si solar cells.

Process	V$_{oc}$ (mV)	J$_{sc}$ (mA/cm²)	FF (%)	η (%)
Reference process (Al-BSF)				
Avrg. (15 cells)	608 ± 2	33.8 ± 0.3	78.5 ± 0.7	16.1 ± 0.2
Best	611	33.8	79.4	16.4
PERC cells with PECVD AlOx + SiNx passivation stack				
Avrg. (23 cells)	617 ± 3	34.6 ± 0.2	77.0 ± 1.2	16.5 ± 0.3
Best	620	34.7	77.8	16.8

An increase of the open-circuit voltage (V$_{oc}$) of about 1.5 % relative and an important increase of the short-circuit current (I$_{sc}$) of about 2.5 % relative is observed for the solar cells passivated with PECVD aluminum oxide compared to the Al-BSF references. However the fill factor of the AlO$_x$/SiN$_x$ rear passivated solar cells lacks slightly behind the Al-BSF solar cells, mainly due to a higher series resistance.

3.4 Internal quantum efficiency (IQE) and light beam induced current (LBIC) measurements

The internal quantum efficiency was measured on one (neighboring) solar cell of each group. The measurement was performed on the complete solar cell area under 0.3 suns bias light. We observe an important increase of the IQE 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 the PECVD AlO_x+SiN_x stack layer on the rear.
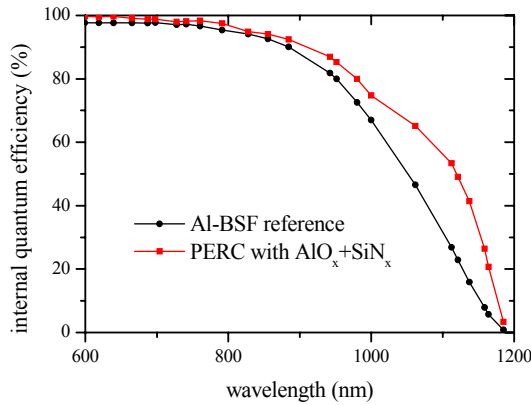

Figure 4: Internal quantum efficiency comparison of PERC-type and Al-BSF cells in the long wavelength range.

The superiority of the AlOx-passivated rear side is also underlined by LBIC current distribution measurements at 977 nm laser wavelength of corresponding Al-BSF (Figure 5, left) and AlO_x rear passivated PERC type solar cells (Figure 5, right).
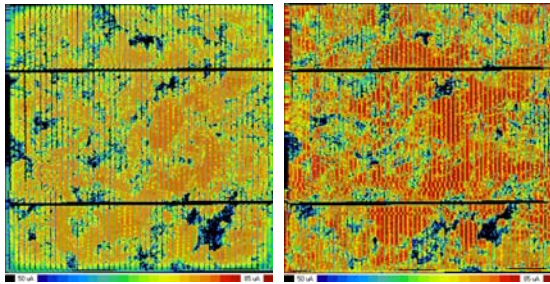

Figure 5: LBIC current distribution at 977 nm laser wavelength for an Al-BSF (left) and AlO_x rear passivated PERC type solar cell (right).

3.4 Variation of rear contact structure

For optimum performance of solar cells featuring a locally contacted rear surface, the metallization fraction as well as the size and distribution of the local contacts are crucial, since ohmic and recombinative losses have to be balanced. As in this work, the laser-fired contact (LFC) technology is applied to form the local rear contacts, optimization of the local rear contact spacing helps to minimize lateral resistance losses. Figure 6 summarizes the influence of a variation of the rear LFC contact pitch on the IV characteristic. In this investigation no influence of a varying contact pitch to the cells' conversion efficiencies is observable. Larger contact pitch results in a slight decrease of the fill factor,

mainly due to an increase in series resistance induced by lateral resistance losses within the semiconductor (spreading resistance) as well as within the screen-printed metal layer. The open circuit voltage increases with increasing pitch because of a lower recombination rate (decreased surface recombination) due to the reduction of the metalized rear surface area.
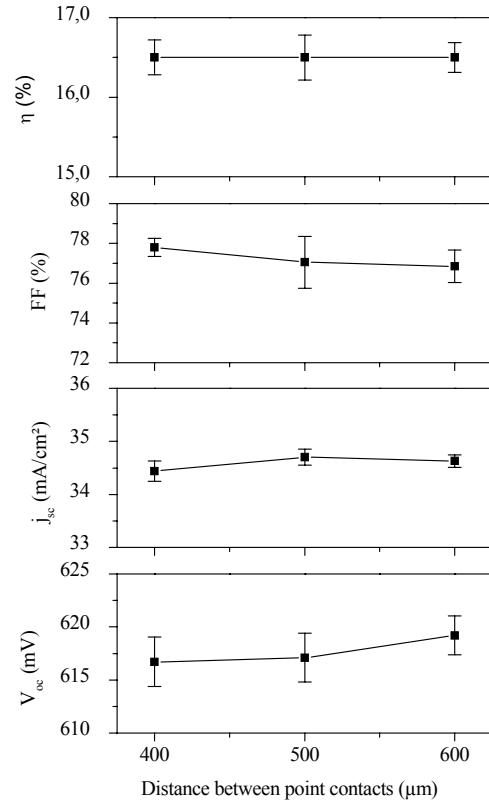

Figure 6: Influence of a variation of the LFC contact pitch on the IV characteristic for the PERC-type mc-Si solar cells investigated.

4 CONCLUSION

The paper reports on current investigations concerning the industrial implementation of PECVD AlO_x stack layers for rear passivation of mc-Si solar cells. It could be demonstrated, that for this purpose, the PECVD technique offers a fast, cost-effective and high quality solution. Layer homogeneities over the full deposition range below 10 % deviation and measured carrier lifetimes well above 500 µs (after annealing) have been reached. Screen printed PERC type mc-Si solar cells implementing a stack passivation layer consisting of AlO_x + SiN_x at the rear and Laser-Fired Contacts have been fabricated and compared to standard Al-BSF references. A gain in open-circuit voltage of about 1.5 % relative and in short-circuit current of about 2.5 % relative could be achieved. As the wafers front side was kept unchanged for PERC-type cells as well as Al-BSF references, the achieved gain can be completely attributed to the passivated and locally contacted rear side. These findings are well supported by additional internal quantum efficiency and LBIC measurements.

5   ACKNOWLEDGEMENT

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