HIGH-EFFICIENCY INDUSTRIAL-TYPE PERC SOLAR CELLS APPLYING ICP AlOₓ AS REAR PASSIVATION LAYER

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ABSTRACT: Passivated emitter and rear cells (PERC) are considered to be the next generation of industrial-type screen-printed silicon solar cells. However, today there exist only few deposition methods for rear passivation layers which meet both, the high-throughput and low-cost requirements of the PV industry in combination with high-quality surface passivation properties. In this paper, we evaluate and optimize a novel deposition technique for AlOₓ passivation layers applying an inductively coupled plasma (ICP) plasma-enhanced chemical vapour deposition (PECVD) process. The ICP AlOₓ deposition process enables high deposition rates of up to 5 nm/s as well as excellent surface recombination velocities below 10 cm/s after firing. When applied to PERC solar cells the ICP AlOₓ layer is capped with a PECVD SiNx layer. We achieve independently confirmed conversion efficiencies of up to 20.1% for large-area (15.6x15.6 cm²) PERC solar cells processed at ISFH with screen-printed metal contacts and ICP AlOₓ/SiNx rear side passivation on standard boron-doped Czochralski-grown silicon wafers. The internal quantum efficiency reveals an effective rear surface recombination velocity S_rear of (90 ± 30) cm/s and an internal rear reflectance Rb of (91 ± 1)% which demonstrates the excellent rear surface passivation of the ICP AlOₓ/SiNx layer stack. PERC solar cells processed in the Q-Cells Research Line achieve efficiencies up to 19.6% with ICP AlOₓ/SiNx rear passivation which is comparable to the reference process at Q-Cells.

Keywords: silicon solar cells, rear passivation, inductively coupled plasma, aluminium oxide, AlOₓ, screen printing

1 Introduction

Passivated emitter and rear (PERC) solar cells are a very promising candidate for next-generation industrial-type screen-printed silicon solar cells. Excellent conversion efficiencies above 20.0% with record values up to 20.2% have been demonstrated by several companies and research institutes for large area, p-type PERC solar cells with screen-printed metal contacts [1,2,3,4]. Several production-type tools for the deposition of rear passivation layers are already available on the market [5,6] or under development [7,8]. In particular, rear passivation layers consisting of aluminium oxide (AlOₓ) have attracted considerable attention due to their excellent surface passivation properties.

However, in addition to excellent electrical properties, it is also important that the AlOₓ deposition process achieves high deposition rates and hence a high throughput which enables a low cost of ownership. Plasma-enhanced chemical vapour deposition (PECVD) processes applying an inductively coupled plasma (ICP) form a high-density plasma (HDP) with electron densities of around 10¹² cm⁻³ [9] and hence allow high deposition rates of up to several nanometres per second [10]. ICP PECVD processes have been intensively investigated for the deposition of dielectric insulation and encapsulation layers consisting of SiO₂ [11,12] or SiNx [12,13,14]. The focus at that time was on applications in microelectronic manufacturing, e.g. as a final passivation layer or diffusion barrier. One important feature of the ICP-PECVD process is that the plasma density can be independently varied from the ion energy, which is typically lower than 30 eV. Hence, an independent optimization of the deposition rate versus the reduction of surface damage of the silicon wafer is possible. In recent years, Singulus Technologies commercialized the ICP-PECVD process for the deposition of SiNx antireflection layers of silicon solar cells using their SINGULAR tool platform [10].

In this paper, we investigate the application of the ICP-PECVD process for the deposition of AlOₓ layers. We deposit the ICP AlOₓ layers using a laboratory-type tool at ISFH and investigate the surface passivation properties. We apply ICP AlOₓ/SiNx layer stacks as rear passivation to large-area PERC solar cells processed at ISFH as well as PERC cells processed at the Q-Cells Research Line. Finally, we present ISFH PERC cell results with an ICP AlOₓ/SiNx layer stack deposited in a SINGULAR production type tool developed by Singulus.

2. AlOₓ deposition using an inductively coupled plasma (ICP)

The ICP AlOₓ layers are deposited in a laboratory-type clustertool (Von Ardenne CS 400 P) at ISFH consisting of a load lock chamber, a transfer chamber and several PECVD deposition chambers including the ICP AlOₓ chamber. Figure 1 displays a schematic drawing of the ICP AlOₓ deposition chamber. A coil outside the vacuum chamber inductively excites the plasma using a high frequency generator with 13.56 MHz. As precursor gas we use trimethylaluminium (TMAI) and as a reactive gas oxygen (O₂). The silicon wafer is transported on a carrier and electrically heated during the AlOₓ deposition. Depending on the process parameters, we obtain high static deposition rates up to 5 nm/s while maintaining low ion energies below 30 eV. We vary the thickness of the resulting ICP AlOₓ layers by adjusting the time of the deposition process. Afterwards, the ICP AlOₓ passivation...
layers are covered with a µW-PECVD SiNy capping layer (SINA, Roth und Rau, or Singular, Singulus) in order to improve the firing stability and the optical reflectivity when applied to PERC solar cells.

**Figure 1**: Schematic drawing of the laboratory-type ICP AlOx deposition chamber. The plasma is inductively excited with a coil outside the vacuum chamber using TMAI and O2 as process gases. The wafer is transported on a carrier and heated during deposition.

3 Surface passivation properties of ICP AlOx layers

**Figure 2**: Effective carrier lifetime and corresponding surface recombination velocity measured on 1.4 Ωcm float zone (FZ) wafers in dependence of the ICP AlOx layer thickness showing lifetimes of up to 2 ms and surface recombination velocities below 10 cm/s for ICP AlOx/SiNy layer stacks after firing.

In order to determine the surface passivation properties, we deposit ICP AlOx layers capped with a µW-PECVD SiNy layer (SINA, Roth und Rau) on both sides of p-type 1.4 Ωcm float zone (FZ) wafers and apply a typical firing process in a conveyor belt furnace with peak temperatures of 910°C. Afterwards we measure the minority charge carrier lifetime using the quasi-steady-state photoconductance (QSSPC) technique at a carrier density of 1x10{15} cm\(^{-3}\). From the measured lifetime \(\tau_{\text{eff}}\), we deduce the maximum surface recombination velocity \(S_{\text{max}}\) attributing the whole recombination to the wafer surface by using the equation \(S_{\text{max}} = W/2*\tau_{\text{eff}}\), where W is the wafer thickness. The QSSPC measurements reveal excellent effective lifetimes of up to 2 ms corresponding to surface recombination velocities (SRV) \(S_{\text{max}}\) below 10 cm/s for ICP AlOx/PECVD SiNy layer stacks after firing as displayed in figure 2. The error bars in figure 2 refer to the minimum and maximum values of the effective lifetimes measured on different positions on the same wafer revealing a good homogeneity of the surface passivation across the wafer. We see a moderate dependence of the SRV on the AlOx layer thickness with the lowest value of 7.5 (±1.5) cm/s at 15 nm AlOx thickness.

4 Application of ICP AlOx/SiNy layer stacks to high-efficiency screen-printed PERC cells processed at ISFH

Figure 3: Schematic drawing of the PERC solar cells processed at ISFH with screen-printed front and rear contacts applying a ICP AlOx/SiNy rear passivation stack.

We apply the ICP AlOx/SiNy layer stacks as rear surface passivation to industrial type high-efficiency PERC solar cells with screen-printed metal front and rear contacts which are processed at ISFH. The process sequence of the PERC solar cells is very similar to the process sequence reported in detail in Ref. 15. Here we just highlight the most important process steps. We use industry-standard 156 x 156 mm\(^2\), boron-doped Czochralski (Cz) silicon wafers with a resistivity of 2 – 3 Ωcm and a starting thickness of 200 µm. Before texturing and phosphorus diffusion, we deposit a dielectric protection layer on the rear side of the wafer leaving the rear side planar and non-diffused. We use a homogeneously doped phosphorus emitter with a sheet resistance of about 60 Ω/sq.

Afterwards, we deposit an AlOx layer on the rear side with the ICP-PECVD deposition process as described above. We evaluate two different ICP AlOx layer thicknesses of 20 nm and 30 nm and compare them to a 10 nm thick ALD Al2O3 layer as reference. We then deposit a µW-PECVD SiNy (SINA, Roth und Rau) capping layer on top of the AlOx passivation layer at the rear in order to improve both, the optical reflectivity as well as the surface passivation quality. Alternatively we deposit an ICP-PECVD SiNy (Singular, Singulus) capping layer. Finally, we apply an ICP AlOx/I CP SiNy layer stack with 30nm AlOx thickness deposited completely in a SINGULAR production type tool developed recently by Singulus

The emitter is covered with a SiNx anti-reflective coating. The dielectric layer stacks at the rear are locally ablated by laser contact opening (LCO) in order to form local line openings [16,17]. We choose line contacts instead of point contacts since line openings facilitate the formation of a deep and uniform local Al-BSF [18]. The Ag front contacts are deposited by a print-on-print (PoP) screen printing process resulting in a finger width of around 70 µm and a shadowing loss including bus bars of around 6.2% [19]. The Al rear contact is formed by full-area Al screen printing applying a commercially available Al paste designed for local rear contacts. A schematic
The drawing of the cross section of the resulting PERC solar cell is shown in figure 3 whereas figure 4 displays photographs of the front and rear side. The contact lines at the cell rear side as well as the rear passivation layer are clearly visible.

Table 1 summarizes the IV parameters of the best solar cells of each split group. The PERC solar cell with a 30 nm ICP AlOx layer achieves an independently confirmed conversion efficiency of 20.1% which is one of the highest efficiencies reported so far for industrial-type PERC solar cells. The high $V_{oc}$ of 655 mV and high $J_{sc}$ of 39.0 mA/cm² indicate the excellent rear side passivation by the ICP AlOx/µW SiNy stack. The PERC solar cells with the 20 nm ICP AlOx layer exhibits similar IV parameters for both, µW (SiNA, Roth und Rau) and ICP SiNy (Singular, Singulus) capping layers. The SINGULAR ICP AlOx/ICP SiNy stack achieves efficiencies up to 19.8% and the reference PERC solar cell with ALD Al2O3/SiNy rear passivation displays efficiencies up to 20.0%. Within statistical process variations and measurement errors, all rear passivation stacks show comparable results. Table 1 also includes the IV parameters of an industry standard screen-printed solar cell with full-area Al-BSF with a conversion efficiency of 18.7%. As can be seen by comparison, the strong efficiency improvement of the PERC solar cells compared to the full-area Al-BSF cell is mainly due to improved $V_{oc}$ and $J_{sc}$ values as a result of the improved electrical and optical properties of the rear side.

Table 1: IV parameters measured under standard testing conditions (STC) of 156 x 156 mm² p-type Cz PERC silicon solar cells processed at ISFH. The ICP AlOx/SiNy passivated cells achieve conversion efficiencies up to 20.1%.

<table>
<thead>
<tr>
<th>AlOx/SiNy</th>
<th>AlOx [nm]</th>
<th>$\eta$ [%]</th>
<th>$V_{oc}$ [mV]</th>
<th>$J_{sc}$ [mA/cm²]</th>
<th>FF [%]</th>
</tr>
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<tbody>
<tr>
<td>ICP/µW</td>
<td>30</td>
<td>20.1*</td>
<td>655</td>
<td>39.0</td>
<td>78.8</td>
</tr>
<tr>
<td>ICP/µW</td>
<td>20</td>
<td>20.0*</td>
<td>657</td>
<td>39.1</td>
<td>77.8</td>
</tr>
<tr>
<td>ICP/SiNy</td>
<td>20</td>
<td>19.9</td>
<td>650</td>
<td>39.2</td>
<td>78.3</td>
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<tr>
<td>SINGULAR</td>
<td>30</td>
<td>19.8</td>
<td>652</td>
<td>38.9</td>
<td>78.1</td>
</tr>
<tr>
<td>ALD/Icp</td>
<td>10</td>
<td>20.0</td>
<td>652</td>
<td>39.3</td>
<td>78.3</td>
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<tr>
<td>Al-BSF</td>
<td>-</td>
<td>18.7</td>
<td>638</td>
<td>37.1</td>
<td>79.1</td>
</tr>
</tbody>
</table>

*Independently confirmed by HfG-ISe CalLab

Figure 5 shows the internal quantum efficiency (IQE) and reflectance of the PERC solar cells of table 1. By analytical modeling we obtain $S_{rear}$ values of 60 – 120 cm/s and an $R_b$ of 90 – 92% showing the excellent electrical and optical properties of the ICP AlOx/SiNy passivation stacks.

5 PERC solar cells with ICP AlOx rear passivation processed at Q-Cells

In addition to the PERC cells processed at ISFH, we apply the ICP AlOx process as rear passivation layer to PERC cells processed in the Q-Cells Research Line. We use 156 x 156 mm² p-type Cz as well as p-type multicrystalline silicon wafers. The solar cells are processed at Q-Cells up to the process step where the rear passivation layer is deposited. We then deposit the ICP AlOx layer in the laboratory-type tool at ISFH on the rear side of the PERC cells. Back at Q-Cells, a SiNy capping layer is deposited on top of the ICP AlOx layer. The cell processing further includes full area Al screen printing on the rear as well as screen-printed Ag front contacts. The rear contacts are formed by laser fired contacts (LFC) [2,23]. In parallel, reference PERC cells are processed in the Q-Cells Research Line for all process steps including a reference rear surface passivation.

Table 2 summarizes the resulting solar cell parameters. Shown are the median values of 8 solar cells of the ICP AlOx/SiNy rear passivated cells as well as the median values of approx. 50 reference PERC cells. In general, the IV parameters of the ICP AlOx/SiNy passivated PERC cells are quite comparable to the reference process and
Passivation stack demonstrate conversion efficiencies up to 19.6% with ICP AlOx/SiNy rear passivation which compares to 19.8% as the best value for the reference cells.

<table>
<thead>
<tr>
<th>Rear Passivation</th>
<th>Wafer type</th>
<th>η [%]</th>
<th>$V_{oc}$ [mV]</th>
<th>$J_{sc}$ [mA/cm²]</th>
<th>FF [%]</th>
</tr>
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<tbody>
<tr>
<td>ICP AlOx</td>
<td>Cz</td>
<td>19.4</td>
<td>640</td>
<td>38.5</td>
<td>78.8</td>
</tr>
<tr>
<td>Reference</td>
<td>Cz</td>
<td>19.5</td>
<td>641</td>
<td>38.4</td>
<td>79.4</td>
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<tr>
<td>ICP AlOx</td>
<td>Multi</td>
<td>17.5</td>
<td>629</td>
<td>36.5</td>
<td>76.5</td>
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<tr>
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<td>17.9</td>
<td>635</td>
<td>36.5</td>
<td>76.8</td>
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</tbody>
</table>

6 Conclusions

We have developed a novel deposition technique for AlOx layers applying an inductively coupled plasma (ICP) PECVD deposition process which allows high deposition rates up to 5 nm/s. Experiments on test wafers demonstrate an excellent surface passivation quality of the resulting ICP AlOx layers with surface recombination velocities after firing down to 7.5 cm/s when applying a SiNy capping layer. Industrial-type PERC solar cells (ICP) PECVD deposition process which allows high deposition rates up to 5 nm/s. Experiments on test wafers demonstrate an excellent surface passivation quality of the resulting ICP AlOx layers with surface recombination velocities after firing down to 7.5 cm/s when applying a SiNy capping layer. Industrial-type PERC solar cells processed at ISFH applying an ICP AlOx/SiNy rear passivation stack demonstrate conversion efficiencies up to 20.1% which is one of the highest conversion efficiencies reported so far for industrial-type PERC solar cells. The IQE analysis reveals an excellent rear surface recombination velocity of (90±30) cm/s and a high internal optical reflectance of (91±1)% in 10%. In addition, PERC solar cells processed in the Q-Cells Research Line with ICP AlOx/SiNy rear passivation achieve median conversion efficiencies of 19.4% on Cz wafers which is very comparable to the reference process with 19.5%. Accordingly, we demonstrate that the ICP-PECVD process is very well suited for the deposition of high quality AlOx passivation layers. Singulus Technologies commercializes this novel passivation layer in the course of this year.

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References