ABSTRACT

Thick thermal oxides of more than 100 nm are commonly used for the production of high-efficiency silicon solar cells from mono- and multicrystalline silicon and have led to the highest conversion efficiencies reported so far. This superior performance of oxides is due to the very good surface passivation by the reduction of the density of interface states. The process to achieve such thick oxides are usually performed at high temperatures for a long time. In this paper we investigate different rear stack systems of a thin thermally grown silicon oxide and PECVD silicon nitride and PECVD silicon oxide layers for rear surface passivation. In a comparatively easy high-efficiency process with laser fired rear contacts (LFC) efficiencies above 20 % for FZ-Si and 18.2 % for multicrystalline silicon were achieved.

INTRODUCTION

In order to increase the cost effectiveness of solar cells from mono- and multicrystalline silicon the efficiencies have to be increased and wafer thickness has to be decreased. One crucial component of the cell to improve the performance is the rear surface due to the increasing demands on optical (internal reflection) and electrical quality (surface passivation). Thick thermal oxides in the range of 100 nm produced at high temperatures and locally defined contacts are commonly used to meet these requirements. They have led to the highest conversion efficiencies on monocrystalline silicon so far [1]. A technological modification is the use of pyrogenic steam to enhance the growth rate and/or reduce oxidation temperature. The latter is especially beneficial for high-temperature sensitive material and has enabled the first multicrystalline silicon solar cells exceeding 20% efficiency [2]. But an oxidation in a tube furnace always takes place on both sides of the wafer and good antireflection properties usually require the removal of the oxide from the front.

One possibility to circumvent this problem would be the one-sided passivation of the rear by a layer deposition technique, e.g. with a PECVD silicon nitride. But although excellent surface passivation properties have been achieved, a loss in $J_{SC}$ is usually observed. The reason is found in the passivation mechanism which mainly uses the field effect. The induced floating junction is shunted by the contact [3] and the passivation is severely reduced under operating conditions. For oxide passivated cells recombination at the rear is mainly suppressed by the reduction of the density of interface states and is therefore not affected by the local contacts. This leads to the superior performance of the oxide.

One solution to the problems mentioned above is the application of a thin thermal oxide which simultaneously passivates the rear and the emitter on the front and is thin enough to allow for excellent antireflection properties in combination with an additional antireflection layer. In order to form a mirror-like rear and to protect the thin oxide, a PECVD silicon nitride layer and a PECVD silicon oxide layer are placed between the thin oxide and the evaporated aluminum. This increases temperature stability and reflectivity of the stack system.

In this paper we compare different rear contacting schemes experimentally:

- evaporated aluminum
- aluminum back surface field created via co-diffusion of evaporated aluminum and emitter diffusion
- PECVD-silicon nitride/PECVD-silicon oxide stack
- thin thermal oxide/PECVD-silicon oxide stack
- thin thermal oxide/PECVD-silicon nitride/PECVD-silicon oxide stack
- thick thermal oxide

The related local contacts were formed with the industrial feasible laser-fired-contact process (LFC) [4].

REAR SURFACE CONTACT SYSTEMS

The basic demands on a suitable rear contacting scheme are:

- high internal reflectance for a good light trapping
- very good rear surface passivation under operating conditions to achieve high $V_{OC}$ and $J_{SC}$ values

These topics are addressed in the following with measurements of effective minority carrier lifetimes and solar cells with a high-efficiency front structure. The latter enables a high performance and a quantitative analysis of significant rear surface properties.

Internal reflectance

The internal reflectance should be as high as possible to enable a good light trapping in co-operation with a well textured front. The reflectance values from 350 µm thick solar cells with a planar front and differently covered rear are shown in Fig. 1.
Fig. 1: Reflectance values of solar cells with differently covered rear surfaces. The front is planar and covered with a double-layer antireflection coating. The dots represent experimental data, the lines are PC1D-simulations.

The highest reflectance values are achieved for the surfaces that are covered with a thick thermal oxide or a thin thermal oxide/silicon nitride/PECVD silicon oxide stack. The reflectance of more than 90% for long wavelength photons is very high and would allow for very good light trapping in textured cells.

When the aluminum is evaporated directly on top of the silicon the reflectance is reduced to 80% and for the rather rough co-diffused aluminum back-surface-field to only 50%. The low reflectivity of the evaporated aluminum without a dielectric layer as well as the low reflectivity of the rough co-diffused aluminum are too low for an effective light trapping.

**Surface passivation**

Besides the optical properties the passivation quality of the rear surface contact scheme is of very high importance. The cells have an identical planar front and are covered with a double layer antireflection-coating. The rear is covered with the same contact schemes as in the previous section. The external quantum efficiencies are shown in Fig. 2.

For determination of the rear surface properties the measured quantum efficiencies were modeled using PC1D [5]. The experimental data was modeled by adjusting the values for bulk lifetime and rear surface recombination velocity. The best fits were obtained with parameter combinations of bulk lifetimes/rear surface recombination velocities of $372 \mu s/200$ cm/s for the oxidized cell, $372 \mu s/300$ cm/s for the stack system, 94 $\mu s/1800$ cm/s for the aluminum co-diffused sample and 34 $\mu s/10^6$ cm/s for the evaporated aluminum. In order to model the measured data of the cells that are in full contact with aluminum adequately, it was not sufficient to increase the $S_{\text{rear}}$ values only but also the bulk lifetime had to be chosen lower (see Fig. 2). This might be due to a small contamination that occurred during evaporation of the layer.

![Fig. 2: External quantum efficiency of planar solar cells with identical front. The rear system varies, the influence of rear passivation can be deduced from the long wavelength response. The dots represent experimental data, the lines are PC1D-simulations.](image2)

![Fig. 3: Combinations of $S_{\text{rear}}$ and $L_{\text{bulk}}$ values for a given effective diffusion length $L_{\text{eff}}$ as it was extracted from the internal quantum efficiency. The crosses show the best fits of the PC1D simulation.](image3)

To verify the results of the PC1D simulation and to check the uniqueness the internal quantum efficiency was used to determine the effective diffusion length by plotting the IQE against the penetration depth $\alpha$

$$IQE^{-1} = 1 + \frac{1}{\alpha \cdot L_{\text{eff}}} \cdot (1)$$

For this effective diffusion length $L_{\text{eff}}$ there exist several combinations of $L_{\text{bulk}}$ and $S_{\text{rear}}$ (Fig. 4) for a fixed thickness $W$ and diffusion constant $D$ given by [6]:

$$L_{\text{eff}} = L_{\text{bulk}} \cdot \frac{1 + S_{\text{rear}} L_{\text{bulk}} / D \cdot \tanh W / L_{\text{bulk}}}{S_{\text{rear}} L_{\text{bulk}} / D + \tanh W / L_{\text{bulk}}} \cdot (2)$$
The bulk lifetime of the PC1D simulation was converted to a bulk diffusion length and the corresponding $S_{\text{rear}}$ values for the given diffusion length in the bulk are given in Table 1. For the same diffusion length in the bulk as derived from the PC1D simulations the results for the dielectrically passivated samples and the co-diffused aluminum agree well between these two methods. For the evaporated aluminum rear the bulk diffusion length is too low to determine a value for $S_{\text{rear}}$ with this method.

Table 1: Effective rear surface recombination velocities of planar solar cells (1 Ω cm FZ, 350 µm thickness). The values were determined by fitting of the EQE in PC1D and by evaluation of the $L_{\text{eff}}$ values for given $L_{\text{bulk}}$.

<table>
<thead>
<tr>
<th></th>
<th>$L_{\text{bulk}}$ [µm]</th>
<th>$S_{\text{rear}}$ [cm/s]</th>
<th>$L_{\text{eff}}$ [µm]</th>
<th>$S_{\text{rear}}$ ($L_{\text{bulk}}$) [cm/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>thick thermal oxide</td>
<td>1000</td>
<td>200</td>
<td>1170</td>
<td>200</td>
</tr>
<tr>
<td>thin oxide / SiN/PECVD-SiO$_x$</td>
<td>1000</td>
<td>300</td>
<td>970</td>
<td>300</td>
</tr>
<tr>
<td>co-diffused aluminum BSF</td>
<td>500</td>
<td>1800</td>
<td>370</td>
<td>2200</td>
</tr>
<tr>
<td>evaporated aluminum</td>
<td>300</td>
<td>$10^6$</td>
<td>210</td>
<td>not determinable</td>
</tr>
</tbody>
</table>

Table 2: Parameters of planar solar cells under standard testing conditions. The size of the cells is 21 cm$^2$, the material used was 350 µm thick FZ of 1 Ω cm base resistivity.

<table>
<thead>
<tr>
<th></th>
<th>$V_{\text{OC}}$ [mV]</th>
<th>$j_{\text{SC}}$ [mA/cm$^2$]</th>
<th>FF [%]</th>
<th>$\eta$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>thick thermal oxide</td>
<td>652</td>
<td>37.1</td>
<td>78.9</td>
<td>19.1</td>
</tr>
<tr>
<td>thin oxide / SiN/PECVD-SiO$_x$</td>
<td>647</td>
<td>36.8</td>
<td>78.3</td>
<td>18.6</td>
</tr>
<tr>
<td>co-diffused aluminum BSF</td>
<td>633</td>
<td>36.3</td>
<td>78.6</td>
<td>18.0</td>
</tr>
<tr>
<td>evaporated aluminum</td>
<td>620</td>
<td>35.1</td>
<td>79.4</td>
<td>17.2</td>
</tr>
</tbody>
</table>

The efficiencies of the manufactured solar cells are presented in Table 2. The best results are achieved by the thick thermal oxide and the reduced values of the other contact schemes can be explained by the optical and electrical properties described in the previous part. Especially the only slight loss of the stack system is promising and will be evaluated in the following section.

### PASSIVATED REAR STACK SYSTEMS

As shown in the previous section a dielectric passivation of the rear is very beneficial and the stack system of the thin thermal oxide/silicon nitride is well suited to do this job in high-efficiency silicon solar cells. The question arises: Is the thin oxide really necessary or does the silicon nitride also work when applied directly on the bare silicon surface? The passivation of silicon nitride directly on top of the silicon is as good as with a thin oxide underneath (see Fig. 4) and should allow for the same performance as rear passivation in a solar cells.

![Effective carrier lifetime of 1 Ω cm FZ-silicon passivated by silicon nitride with and without underlying thin thermal oxide after a forming gas anneal at 350 °C for 15 minutes.](image)

The optical properties are also hardly changed since the additional PECVD silicon oxide enhances the reflectivity of the stack system. However, in a working solar cell the achievable short-circuit current densities are greatly reduced. Dauwe et al. [3] gave the explanation as the shunting of induced inversion layer by the rear contact. Therefore under $V_{\text{OC}}$ conditions (like in the carrier lifetime measurements) the passivation is fully in operation whereas under working conditions the rear is shunted and a great loss in $j_{\text{SC}}$ is observed due to the loss in passivation. This was observed for our cells, too (see Fig. 5) and is due to the structure of the used silicon nitride that passivates via the field effect. If other silicon nitride compositions are used, this effect can be greatly reduced and has already lead to a 19.3 % efficient solar cell with the same cell structure as used in this study [7] and efficiencies in excess of 20 % were reported by Dauwe et al. [8] and higher than 21% by Glunz et al. [9] with slightly different solar cell structures.

Now the question arises: Why do we need the nitride? Does it lead to a hydrogenation of the silicon/silicon oxide interface? To answer this question another batch of high-efficiency solar cells with textured front and oxide passivated rear was fabricated. The emitter is driven-in and passivated with a thick thermal oxide. This process was chosen to have a high-efficiency front surface that does not limit the cell performance and allows to clearly see the effect of the rear. The rear differed in the choice of
the stack system. For one part the thin oxide was covered directly with a PECVD silicon oxide of about 100 nm, for another part a hydrogen passivation was performed in a remote plasma reactor before PECVD silicon oxide deposition, the third quarter was covered with the silicon nitride / PECVD silicon oxide stack and the reference cells had a thermal oxide of about 100 nm (Fig. 6). The results are shown in Table 3.

The best cells are achieved by the thick thermal oxide and shows the highest potential of the solar cells. In comparison to this reference, the $V_{OC}$ and $j_{SC}$ values are reduced for the stack systems but this effect is due to the slightly worse passivation and not due to shunting of the inversion layer since surface the major fraction of the passivation is achieved by the thin oxide. The silicon nitride was expected to improve the performance of the solar cells in comparison to the solely thin oxide / PECVD-silicon nitride stack due to a hydrogenation effect of the silicon/silicon oxide interface. Nevertheless, in this study we have no significant experimental evidence that a supplemental hydrogenation takes place, neither by the silicon nitride nor by the hydrogen passivation from a plasma reactor.

The effect of the aluminum anneal in forming gas is sufficient to lead to a well passivated rear. Therefore the nitride does not seem to be necessary and, from this point of view, could be omitted for a future cell design on monocrystalline silicon.

**Application to multicrystalline silicon**

The thin thermal oxide/silicon nitride/PECVD silicon oxide stack system was also applied on standard quality 1.5 $\Omega$ cm multicrystalline silicon produced by ScanWafer. In this case the surface texturing was performed with a plasma texturing process [10]. During emitter diffusion the rear was covered by a PECVD silicon oxide to prevent a phosphorus diffusion and was etched off afterwards. Then the wafers were shortly oxidized in a tube furnace to achieve an oxide thickness of about 10 nm on front and rear. After that the rear was covered by a thin silicon nitride of about 20 nm and the PECVD silicon oxide of about 50 nm thickness.

### Table 4: Parameters of plasma textured solar cells under standard testing conditions. The size of the cells is 1 cm$^2$, the material used was 1 $\Omega$ cm FZ and 1.5 $\Omega$ cm multicrystalline silicon of 250 µm thickness.

<table>
<thead>
<tr>
<th></th>
<th>$V_{OC}$ [mV]</th>
<th>$j_{SC}$ [mA/cm$^2$]</th>
<th>FF [%]</th>
<th>$\eta$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>mc-silicon wet oxide</td>
<td>633</td>
<td>38.0</td>
<td>79.1</td>
<td>19.0</td>
</tr>
<tr>
<td>FZ-silicon wet oxide</td>
<td>644</td>
<td>38.8</td>
<td>82.0</td>
<td>20.5</td>
</tr>
<tr>
<td>mc-silicon stack system</td>
<td>619</td>
<td>37.7</td>
<td>78.0</td>
<td>18.2</td>
</tr>
<tr>
<td>FZ-silicon Stack system</td>
<td>640</td>
<td>38.7</td>
<td>81.2</td>
<td>20.1</td>
</tr>
</tbody>
</table>
The laser firing of the contacts was followed by the evaporation of a double layer antireflection coating and a short forming gas anneal for 15 min at 350 °C. For comparison a wet thermal oxide was used as diffusion barrier and simultaneous rear passivation [2]. This more complex and longer process shows a slightly higher performance (see Table 4).

Temperature stability

The stability of the stack systems during further temperature treatments is an important feature for a high flexibility in process design. The improved stability of oxide/silicon nitride stack systems was shown by Schmidt et al. [11] and Narasimha and Rohatgi [12], the improved stability of silicon nitride when covered by a PECVD-silicon oxide was shown by Hofmann et al. [7]. In our study a forming gas anneal at comparative low temperatures of 350 °C was applied for 15 min and no degradation of the thin thermal oxide/silicon nitride/PECVD silicon oxide stack system with 2 µm aluminum covering was found. Of probably more interest is the stability against high-temperature processes as they occur in the firing step of screen printed front metallization. Therefore lifetime test samples of 1 Ω cm FZ were prepared with two stack systems:

- thin thermal oxide/PECVD-silicon oxide stack
- thin thermal oxide/PECVD-silicon nitride/PECVD-silicon oxide stack

![Fig. 7: Surface recombination velocity of rear passivation stacks before and after a firing step at 795°C. The stack with the silicon nitride drastically improves the thermal stability.](image)

The minority carrier lifetime of the samples was measured before and after a simulated firing step at 795 °C (no metal paste on front, no aluminum on rear) and the effective surface recombination calculated. The results are shown in Fig. 7. The stack with the silicon nitride between the thin thermal oxide and the PECVD silicon oxide has a much better thermal stability than without the silicon nitride. Since the silicon nitride is not necessary for the passivation itself it can rather freely be chosen [11] and adjusted to the demands of temperature stability and hydrogen release during firing, which will probably be beneficial for bulk passivation of multicrystalline silicon solar cells.

CONCLUSION

A stack system of a thin thermal oxide/PECVD silicon oxide has proven to be capable of high-efficiency silicon solar cells in excess of 20 % efficiency. Since only a thin oxide in the range of 10 nm is needed, short oxidation times and comparatively low temperatures are sufficient. This is also beneficial for the application to multicrystalline silicon. A silicon nitride layer can be inserted into the stack system and enhance temperature stability without a significant loss of optical or electrical properties.

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REFERENCES