Experimental Evidence of Parasitic Shunting in Silicon Nitride Rear Surface Passivated Solar Cells

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Many solar cells incorporating SiN \(_x\) films as a rear surface passivation scheme have not reached the same high level of cell performance as solar cells incorporating high-temperature-grown silicon dioxide films as a rear surface passivation. In this paper, it is shown by direct comparison of solar cells incorporating the two rear surface passivation schemes, that the performance loss is mainly due to a lower short-circuit current while the open-circuit voltage is equally high. With a solar cell test structure that features a separation of the rear metal contacts from the passivating SiN \(_x\) films, the loss in short-circuit current can be reduced drastically. Besides a lower short-circuit current, dark I–V curves of SiN \(_x\) rear surface passivated solar cells exhibit distinct shoulders. The results are explained by parasitic shunting of the induced floating junction (FJ) underneath the SiN \(_x\) films with the rear metal contacts. The floating junction is caused by the high density of fixed positive charges in the SiN \(_x\) films. Other two-dimensional effects arising from the injection level dependent SRV of the Si/SiN \(_x\) interfaces are discussed as well, but, are found to be of minor importance. Pinholes in the SiN \(_x\) films and optical effects due to a different internal rear surface reflectance can be excluded as a major cause for the performance loss of the SiN \(_x\) rear surface passivated cells. Copyright © 2002 John Wiley & Sons, Ltd.

INTRODUCTION

The future trend toward lower cell thickness for crystalline silicon solar cells exhibiting diffusion lengths exceeding the cell thickness has increased the demand for low-cost, yet effective rear surface passivation. Amorphous hydrogenated silicon nitride (SiN \(_x\)) deposited by low-temperature (\(\leq 400^\circ\text{C}\)) plasma-enhanced chemical vapour deposition (PECVD) is a promising candidate for achieving this goal.\(^{1,2}\) Very low surface recombination velocities (SRVs) have been obtained with SiN \(_x\) films on low-resistivity (\(~1 \Omega\text{ cm}\)) p-type Si that is frequently used for solar cell processing. The low SRV exhibited by Si/SiN \(_x\) interfaces is due to two very different reasons.\(^{3}\) First, saturation of the dangling bonds at the interface by atomic hydrogen that is released from the precursor gases (SiH \(_4\) and NH \(_3\)) during deposition, decreasing the interface...
state density. And second, field-effect passivation caused by a high density of fixed positive charges in the insulating SiNₓ layer.

For solar cells, SiNₓ films have been used as surface passivating anti-reflection coatings, e.g., for bifacial silicon solar cells, owing to the adjustable refractive index \((n \approx 1.8–2.5)\). The high open-circuit voltage of 649 mV that has been achieved demonstrates the excellent surface passivation provided by the SiNₓ films. Recently, the results of solar cells incorporating SiNₓ films as rear surface passivation have been compared with results of cells incorporating a high-temperature-grown silicon dioxide. Since the passivation of silicon surfaces by thermally grown oxide films is the most common passivation scheme for high-efficiency solar cells today, these cells can be regarded as references. It was found that the open-circuit voltages of the SiNₓ rear surface passivated cells are comparable to the respective silicon dioxide passivated reference cells differing only about 1-0% at the most: Kerr et al. reported open-circuit voltages of 667-3 mV for a planar, all-nitride passivated solar cell and 661 mV for the respective reference cell. The contact openings were defined by photolithography and chemical etching for these cells. Glunz et al. published values of 660 mV for SiNₓ and 661 mV for oxide rear surface passivated solar cells. They performed the patterning of the passivation layer by laser ablation. In the same paper they reported 674 and 678 mV, respectively, for solar cells where the contact pattern was formed by plasma etching. In a recent publication, we reported 654 and 657 mV for cells where the contact openings were defined by mechanical means. Despite these remarkably high open-circuit voltages for SiNₓ rear surface passivated cells, the obtained short-circuit current densities are—in some cases exceptionally—lower compared with the oxide passivated cells. In this respect, Glunz et al. reported, in the case of cells having the laser-ablated rear contact pattern, 37-4 mA/cm² for the SiNₓ and 39-7 mA/cm² for the oxide rear surface passivated cells while we reported 37-1 mA/cm² compared with 39-2 mA/cm². In our previous paper, the lower short-circuit current density \(J_{sc}\) has been fully attributed by us to the injection-level dependence of the SRV at the Si/SiNₓ interface. However, in the present work, experimental evidence is given that there is a further, predominant reason for low \(J_{sc}\) values obtained with SiNₓ rear surface passivated solar cells, namely shunting across the induced floating junction (FJ) at the rear surface. Recently, the results of laser-beam-induced current (LBIC) measurements of bifacial solar cells incorporating an SiNₓ rear surface passivation have been explained by shunt-affected FJ passivation as well. It should be noted that a significant current loss is not observed for all reported cells, indicating that parasitic shunting may be eliminated by using different SiNₓ films or a different method to perform the contact openings.

In this paper, we present results of a solar cell test structure that features a separation of the inversion layer from the metal contacts. This test structure allows the distinction between different loss mechanisms. Besides losses in short-circuit current a further characteristic trait of a shunt across a rear FJ is a shoulder observed in the corresponding dark \(I–V\) curve of the cell. We report on shoulders in dark \(I–V\) curves of SiNₓ rear surface passivated solar cells. Since shoulders in dark \(I–V\) curves can be attributed to an injection-level-dependent SRV of the Si/SiNₓ interfaces as well, an estimation is given for the relevance of each effect.

**CELL STRUCTURE**

MIS-contacted diffused \(n^+p\) junction (MIS-\(n^+p\)) silicon solar cells were fabricated with 0.5 and 1.5 Ω cm FZ \(p\)-type silicon as starting material. The MIS-\(n^+p\) process as described elsewhere was used for the front surface of the cells. The cells have an active area of 4 cm². Three different sets of cells were fabricated in this work, differing only in the rear surface passivation scheme. For the first cell type, SiNₓ films were used to passivate the whole non-metalised area at the rear surface of the cells. These are referred to as PR-SiN cells (passivated rear with SiNₓ). The silicon nitride films were deposited in a remote PECVD reactor at 400°C, with silane, ammonia and nitrogen as precursor gases. As reference, a second set of cells having a high-temperature-\(\sim1000°C\) grown silicon dioxide rear surface passivation were fabricated, referred to as PR- \(SiO\) cells in the text. The rear of the solar cells is schematically shown in Figure 1. For a detailed investigation of two-dimensional effects, additional solar cell test structures were fabricated, characterised by photolithographically defined oxide lines between the SiNₓ films and the contact lines, leaving about 88% of the rear surface passivated by SiNₓ (3% contact area and 9% oxide passivation). Oxide lines of about 200 μm width separate the SiNₓ passivated areas.
from the metal contacts, as sketched by the dotted lines in Figure 1. These cells are referred to as PR-SiN/SiO cells. In this test structure, the inversion layer underneath the SiN_x films is separated from the rear metal contact. The rear contacts are formed by mechanical means for all fabricated solar cells. For a sound comparison of the different cell structures, all cells were fabricated in the same run. It should be noted that since the contact openings are formed by mechanical abrasion, defects are introduced in the crystal between the inversion layer and the contact. The defects may cause current paths, thus enhancing the parasitic shunt conductance. However, PR-SiN cells with rear contact openings realised by photolithography and chemical etching that have been fabricated at ISFH show the same non-idealities as those where the contact openings were formed by mechanical means. Also, samples that received an additional saw damage etch after the abrasion step give the same results. For simplicity, this damage etch was omitted for all cells described in this work.

**SOLAR CELL RESULTS**

The parameters of the fabricated solar cells on 1.5 Ω cm FZ p-type silicon are shown in Table I. The results are mean values of a set of four identical processed samples. For PR-SiN cells $V_{oc}$ is only 6 mV (0.9% relative) smaller than for the reference PR-SiO cells. This can be attributed to the excellent surface passivation of all films at injection levels relevant for $V_{oc}$ (about $10^{15}$ cm$^{-3}$). In contrast, for the short-circuit current density $J_{sc}$ a significant reduction of 1.4 mA/cm$^2$ (4% relative) is observed for the PR-SiN cells compared with the PR-SiO reference cells. By introducing narrow oxide lines to separate the SiN_x passivated areas from the metal contacts this reduction in $J_{sc}$ decreases to only 0.2 mA/cm$^2$, i.e., it is nearly eliminated. The same trend can be seen for the fill factor, but to a lesser extent. In a previous paper, we fully attributed the lower $J_{sc}$ values of the PR-SiN cells to a poorer passivation provided by the SiN_x films compared with SiO_2 films at excess carrier densities relevant for $J_{sc}$ conditions. However, the results for the PR-SiN/SiO cells are clear experimental evidence that additional two-dimensional effects are the predominant influence on cell performance.

Table I. Results for PR-SiO, PR-SiN and PR-SiN/SiO cells measured under AM1.5G, 100 mW/cm$^2$ illumination and at 25°C

<table>
<thead>
<tr>
<th>Type</th>
<th>$V_{oc}$ (mV)</th>
<th>$J_{sc}$ (mA/cm$^2$)</th>
<th>Fill factor (%)</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PR-SiO</td>
<td>649 ± 1</td>
<td>34.5 ± 0.2</td>
<td>80.6 ± 0.2</td>
<td>17.9 ± 0.2</td>
</tr>
<tr>
<td>PR-SiN</td>
<td>643 ± 1</td>
<td>33.1 ± 0.1</td>
<td>78.9 ± 0.3</td>
<td>16.8 ± 0.1</td>
</tr>
<tr>
<td>PR-SiN/SiO</td>
<td>646 ± 1</td>
<td>34.3 ± 0.2</td>
<td>80.2 ± 0.2</td>
<td>17.8 ± 0.1</td>
</tr>
</tbody>
</table>

All samples were processed in the same run. Mean values of four identical processed samples are shown. The substrate material used is 1.5 Ω cm FZ p-type Si with planar front surface.
An explanation of the experimental results follows from the high amount of fixed positive charges that SiN\(_x\) films contain (\(Q_f = 4 \times 10^{11} \text{cm}^{-2}\)) causes weak inversion in thermal equilibrium (assumptions: AM1.5G, 300 K, 300 \(\mu\)m thick 0.5 \(\Omega\)cm \(p\)-type wafer, \(\tau_{\text{bulk}} = 500 \mu\text{s}, S_{\text{front}} = 0 \text{cm/s}, S_{\text{rear}} = 1000 \text{cm/s}\)). For zero shunt conductance calculated values are: \(J_{\text{sc}} = 38.7 \text{mA/cm}^2\), \(V_{\text{oc}} = 684.2 \text{mV}\), \(FF = 81.4\%\).

Figure 2. Calculation of the variation of \(J_{\text{sc}}, V_{\text{oc}}\) and FF with the shunt conductance. The assumed fixed charge density in the passivating rear film of \(Q_f = 4 \times 10^{11} \text{cm}^{-2}\) causes weak inversion in thermal equilibrium (assumptions: AM1.5G, 300 K, 300 \(\mu\)m thick 0.5 \(\Omega\)cm \(p\)-type wafer, \(\tau_{\text{bulk}} = 500 \mu\text{s}, S_{\text{front}} = 0 \text{cm/s}, S_{\text{rear}} = 1000 \text{cm/s}\)). For zero shunt conductance calculated values are: \(J_{\text{sc}} = 38.7 \text{mA/cm}^2\), \(V_{\text{oc}} = 684.2 \text{mV}\), \(FF = 81.4\%\)
Thus, current flow from the inversion layer into the metal contacts is the dominant parasitic effect for PR-SiN cells. A detailed quantitative investigation of the different contributions to the recombination requires additional two-dimensional simulation and will be published elsewhere.

**EVALUATION OF DARK I–V CURVES**

Figure 3(a) shows the dark I–V curves for one sample of each solar cell set (PR-SiN, PR-SiO, PR-SiN/SiO). Shoulders in dark I–V curves can be highlighted as a bump if the inverse slope of the log(I)–V curve is considered, that is the plot of local ideality factor against V ($n_{loc}$) of Figure 3(b). The saturation current for the PR-SiO cell is the lowest and no bump is seen in the $n_{loc}$ curve. For the PR-SiN and the PR-SiN/SiO cells a shoulder in the I-V curves is clearly visible as a bump in the respective $n_{loc}$ curves. The peak of the bump is located at 570 mV (510 mV) for the PR-SiN (PR-SiN/SiO) cell. The decreasing slope in the dark I–V curves (increasing local ideality factor) at higher voltages can be attributed to the series resistance of the cells.

Shoulders in the dark I–V curve are characteristic of a strongly injection-level-dependent SRV at the rear surface. SRVs that are significantly higher at low external voltages, i.e., low injection, than at higher voltages and a transition from high to low SRV occurring over a relatively small injection range, give rise to those shoulders in dark I–V curves. Two very different causes have been proposed for these non-ideal characteristics.19,20 The first cause is the trivial case that the effective SRV of the passivating film/Si interface shows an injection level dependence. Shoulders in dark I–V curves have been reported for high-temperature SiO$_2$ passivated PERL cells, due to the transition from high to low effective SRV with increasing injection level for Si/SiO$_2$ interfaces.19 A second very different cause for the transition from high to low SRV with increasing voltage is a parasitic shunt across a rear FJ.11,20,21 The shunt causes an overall SRV that is injection dependent, even if the interface itself does not show any injection dependence of the SRV. This can be explained as follows.11 Electrons in the inversion layer at the rear can either be injected into the p-type base of the cell, or they can flow through the parasitic shunt resistance into the rear contact, in which case they do not contribute to the cell current. A significant current loss due to the latter case corresponds to a very high overall SRV. Like any junction, when the voltage across the FJ is small, practically all of the current flows through the shunt resistance, whereas when the voltage is high, the main part of the current flows through the diode. The voltage required to cause the transition from shunt-dominated to diode-dominated current flow depends primarily on the magnitude of the shunt resistance.11

A relationship between the voltage across the FJ ($V_{FJ}$) and the voltage across the emitter ($V_{em}$) was calculated by Altermatt et al.22 In the ideal case of no recombination, $V_{FJ} = V_{em}$. If current is lost due to shunts or
recombination at the rear surface, $V_{FJ}$ is lower than $V_{cm}$ at low $V_{em}$ and approaches $V_{em}$ for higher voltages across the emitter. The higher the current loss the higher $V_{em}$ (and therefore external voltage) is required for the transition from shunt- to diode-dominated current flow. Thus, for a small shunt resistance the shoulder occurs at a higher external voltage in the dark $I–V$ curve.

Although the underlying physics is very different for the two possibilities that cause a shoulder in the dark $I–V$ curve, the exhibited non-idealities are very similar, making it difficult to assign certain amounts of the observed non-idealities to either effect. However, the different voltages at which the bumps for the PR-SiN or PR-SiN/SiO cell occur (Figure 3) make it possible to distinguish between the effects. Since the rear effective SRV of the PR-SiN/SiO cells is almost the same as that of the PR-SiN cells, the difference between the two cell types lies only in the increased shunt resistance due to the separation of the inversion layer from the metal contacts. Thus, it can be concluded that the shunting across the FJ is the more significant effect for the PR-SiN cell in accordance with the results presented in the previous section. Owing to the increased shunt resistance for the PR-SiN/SiO cells, the transition from shunt- to diode-dominated behaviour of the cell occurs at lower voltages. However, in contrast to the PR-SiN cell, the shoulder in the dark $I–V$ curve of the PR-SiN/SiO cell is additionally influenced by the strongly injection-level-dependent SRV of the Si/SiNx interface.

**POTENTIAL OF SiN$_x$-PASSIVATED CELLS AND MEANS TO DECREASE THE PARASITIC CURRENT LOSS**

In order to demonstrate the potential of SiN$_x$ passivated cells, the contact spacing at the rear surface is enlarged to focus on the passivation qualities of the different films. A lower fill factor due to a higher series resistance is disregarded. Owing to a better passivation of the rear surface, both $V_{oc}$ and $J_{sc}$ increase with increasing contact spacing as can be seen in Table II. The relative increase of the short-circuit current of the PR-SiN cells is almost a factor of five higher than that of the PR-SiO cells. Again, this can be explained by a shunt resistance across the induced FJ. Owing to the relatively high sheet resistance of the inversion layer, fewer electrons from the inversion layer are collected if the distance to the contact increases.

It is important to note that a major influence of pinholes in the SiN$_x$ films, short-circuiting the inversion layer with the overlying metal film, can be excluded because of the higher $J_{sc}$ of the PR-SiN/SiO (Table I) and the PR-SiN cells with wider contact spacing (Table II) compared with PR-SiO cells. For the same reasons, a major influence of optical effects arising from the different internal reflectances of the rear layer structures can be excluded.

From the above analysis, different means become evident to avoid non-idealities exhibited by PR-SiN cells. First, if the inversion layer sheet resistance is increased by keeping the same low effective SRV, shunting problems can be avoided. This possibility can be achieved with optimised SiN$_x$ films or SiO$_2$/SiN$_x$ double-layers.

<table>
<thead>
<tr>
<th>Cell type</th>
<th>Cell parameter</th>
<th>Narrow contact spacing (optimised for PR-SiO cells)</th>
<th>Wide contact spacing (only three contact lines)</th>
<th>Relative change (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PR-SiO</td>
<td>$V_{oc}$ (mV)</td>
<td>655.6 ± 0.9</td>
<td>657.0 ± 2.0</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>$J_{sc}$ (mA/cm$^2$)</td>
<td>39.01 ± 0.03</td>
<td>39.33 ± 0.16</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>Fill factor (%)</td>
<td>80.2 ± 0.7</td>
<td>78.8 ± 0.4</td>
<td>-1.7</td>
</tr>
<tr>
<td></td>
<td>Efficiency (%)</td>
<td>20.5 ± 0.2</td>
<td>20.4 ± 0.1</td>
<td>-0.5</td>
</tr>
<tr>
<td>PR-SiN</td>
<td>$V_{oc}$ (mV)</td>
<td>652.0 ± 3.7</td>
<td>655.9 ± 2.4</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>$J_{sc}$ (mA/cm$^2$)</td>
<td>36.76 ± 0.61</td>
<td>38.17 ± 0.17</td>
<td>3.8</td>
</tr>
<tr>
<td></td>
<td>Fill factor (%)</td>
<td>80.8 ± 0.2</td>
<td>78.7 ± 0.4</td>
<td>-2.6</td>
</tr>
<tr>
<td></td>
<td>Efficiency (%)</td>
<td>19.4 ± 0.4</td>
<td>19.7 ± 0.2</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Mean values of four cells per cell type are shown. The substrate material used is 0.5 Ω cm FZ p-type Si with textured front surface. In-house measurement under standard AM1.5G, 100 mW/cm$^2$ illumination at 25°C.

respectively, having an excellent SRV and a high inversion layer sheet resistance. A different solution is the introduction of a barrier for electrons between the inversion layer and the metal contact, since the interface between the inversion layer and the contact is a crucial point for the improvement of PR-SiN cells. For this purpose, a local back surface field (LBSF) can be incorporated. The potential step between the $p^{++}$ region underneath the contact and the $n$ inversion layer repels electrons from the back contact. Note that in either case the injection level in contact-adjacent regions is increased, thus decreasing the SRV.

**CONCLUSION**

In conclusion, although PECVD SiN$_x$ films provide excellent passivation, parasitic effects have been identified in this paper that decrease cell performance if SiN$_x$ films are incorporated in a rear surface passivation scheme. Owing to the high fixed positive charge density incorporated in the films an inversion layer is induced, i.e., for SiN$_x$ rear surface passivation the same concepts apply as for a diffused FJ passivation. If no precautions are taken to separate the inversion layer from the metal contacts, parasitic current flow decreases cell performance. Oxide separation of the rear contact areas and the SiN$_x$ passivated areas has been successfully introduced to prevent a parasitic current flow from the inversion layer to the metal contacts, thus improving both cell performance and the understanding of parasitic effects in PR-SiN cells. It has been shown that SiN$_x$ films have the potential of providing an excellent rear surface passivation for silicon solar cells, and means are suggested that are able to reduce parasitic effects that adversely affect cell performance of SiN$_x$ rear surface passivated solar cells. First, SiN$_x$ films that introduce a weaker inversion layer can be used, and research is under way to optimise the films in this respect. Another promising way is the incorporation of a potential barrier between the inversion layer and the metal contacts. This can be obtained by introducing an LBSF into the cell design. An LBSF additionally decreases rear contact recombination, thus providing two-fold advantages. The results reported by Hübner et al. and more recent results at ISFH of a comparison experiment of cells with and without an LBSF confirm the expected beneficial effect of an LBSF on the reduction of the parasitic shunting.

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