17.5% p-Type Silicon Heterojunction Solar Cells with HWCVD a-Si:H as the Emitter and Back Contact

National Renewable Energy Laboratory

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ABSTRACT

Thin hydrogenated amorphous silicon (a-Si:H) layers deposited by hot-wire chemical vapor deposition (HWCVD) are used as both emitters and back contacts in silicon heterojunction solar cells. Low interface recombination velocity and high open-circuit voltage are achieved by a low substrate temperature (<150°C) intrinsic a-Si:H deposition which ensures immediate amorphous silicon deposition. This is followed by deposition of doped a-Si:H at a higher temperature (>200°C) which appears to improve dopant activation. With an i/n a-Si:H emitter, we obtain a confirmed efficiency of 17.1% on textured p-type float-zone (FZ) silicon with a screen-printed aluminum back-surface-field (Al-BSF) contact. Employing a-Si:H as both the front emitter and the back contact, we achieve a confirmed efficiency of 17.5%, the highest reported efficiency for a p-type c-Si based heterojunction solar cell.

1. Introduction

The silicon heterojunction (SHJ) is one of the most attractive device structures for fabrication of high-efficiency silicon solar cells at low temperatures (<250°C) with simple processing. The excellent surface passivation provided by H and extra band bending due to the larger band gap of a-Si:H compared to c-Si makes well-designed a-Si:H emitters superior to conventional emitters made by dopant diffusion. Furthermore, a thin layer of a-Si:H, doped the same as the base wafer provides a back collector with very effective back-surface field that reduces the recombination velocity. The current conduction through the a-Si:H collector is adequate and no localized current conduction windows are needed, in contrast to dielectric back-surface passivation layers. These outstanding properties open the path to many a-Si/c-Si heterojunction silicon solar cell designs, the most successful being the Sanyo HIT cell [1] employing plasma-enhanced chemical vapor deposition (PECVD) to deposit thin p/i (emitter) and n/i (collector) a-Si:H layers on n-type wafers.

Great care must be taken in using PECVD to make high-efficiency SHJ cells because of the potential for plasma damage to the c-Si wafer surfaces. At NREL, hot-wire chemical vapor deposition (HWCVD) is used to eliminate the possibility of such ion damage. We have successfully used this technique to obtain record efficiencies for p-type c-Si wafer based heterojunction solar cells.

2 Results and Discussions

2.1 Single-Heterojunction SHJ Solar Cells – the a-Si:H Emitter

We use a standard Al-BSF on the back to optimize the a-Si:H emitter on the front. In a typical a-Si:H/c-Si heterojunction solar cell, a thin (~4 nm) intrinsic hydrogenated a-Si:H layer is interposed between the base wafer and the heavily doped emitter. Though such thin i-layers are difficult to characterize, i-layers likely have a far lower density of defects and a slightly larger energy gap than doped a-Si:H layers: both factors are advantageous for reducing dark current through the junction and increasing Voc. If inadvertent epitaxy occurs during the i-layer deposition, it is unlikely to be of high quality. Further, if crystallinity extends through the i-layer, the rough c-Si interface can be contacted in places by the doped a-Si:H which is likely a less effective passivant than the i-layer. Any dark-current path through inadequately passivated interface states in a heterojunction solar cell reduces the open-circuit voltage (Voc). Using HWCVD, we vary both the i- and n-layer deposition temperatures (Td) to find the optimum conditions. It turns out that high Voc values with (100) silicon wafers are obtained at temperatures below 150°C, but at temperatures higher than 200°C, Voc is much reduced. This is because epitaxy is usually favored at i-layer deposition temperature Td > 200°C while lower temperature (Td < 150°C) ensures abrupt a-Si:H deposition [2].

With an i-layer deposited at a low temperature of 100°C, we find that raising the n-layer deposition temperature to about 200°C provides the highest Voc (see Figure 1). This seems to provide effective activation of the phosphorous dopant and a better quality n-layer. These optimizations on the a-Si:H emitter lead to 17.1% efficient single-side SHJ solar cells as shown in Table 1. This is a record for p-type c-Si based heterojunction solar cell using an Al back-surface field contact.

Table 1. Confirmed measurements of 1-cm² ITO/a-Si:H/c-Si/Al-BSF single-side solar cells on p-type c-Si substrates

<table>
<thead>
<tr>
<th>ID</th>
<th>Voc(V)</th>
<th>Jsc(mA/cm²)</th>
<th>F.F.(%)</th>
<th>η(%)</th>
<th>Substrate</th>
</tr>
</thead>
<tbody>
<tr>
<td>16C</td>
<td>0.645</td>
<td>33.11</td>
<td>79.2</td>
<td>16.9</td>
<td>1.0 Ω·cm planar FZ</td>
</tr>
<tr>
<td>65C</td>
<td>0.652</td>
<td>32.16</td>
<td>80.5</td>
<td>16.9</td>
<td>0.5 Ω·cm planar FZ</td>
</tr>
<tr>
<td>62A</td>
<td>0.636</td>
<td>34.96</td>
<td>76.8</td>
<td>17.1</td>
<td>1.0 Ω·cm textured FZ</td>
</tr>
</tbody>
</table>
2.2 Double-Heterojunction SHJ Solar Cells – the a-Si:H Back Contact

Applying the best emitter a-Si:H deposition conditions to the backside passivation, we have fabricated simple double-heterojunction SHJ solar cells with a structure of ITO/a-Si:H emitter/c-Si/a-Si:H back contact.

Table 2. Effects of a-Si:H as emitter and back contact on Voc

<table>
<thead>
<tr>
<th>ID</th>
<th>Voc (V)</th>
<th>Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-5</td>
<td>0.63</td>
<td>diffused n+/planar p-FZ/Al-BSF</td>
</tr>
<tr>
<td>16C</td>
<td>0.65</td>
<td>a-Si(n/i)/planar p-FZ/Al-BSF</td>
</tr>
<tr>
<td>1540</td>
<td>0.65</td>
<td>a-Si(n/i)/textured p-FZ/Al-BSF</td>
</tr>
<tr>
<td>2933</td>
<td>0.66</td>
<td>a-Si(n/i)/textured p-FZ/a-Si(i/p)</td>
</tr>
<tr>
<td>2930</td>
<td>0.69</td>
<td>a-Si(p/i)/planar n-FZ/a-Si(i/n)</td>
</tr>
</tbody>
</table>

Table 2 illustrates the successive increases in Voc by replacing a diffused junction with an a-Si:H emitter on the front and replacing an Al-BSF with an a-Si:H contact on the back. On textured 1.3 Ω·cm p-type FZ-Si, with an a-Si:H(i/p) back contact and a-Si(i/n) emitter, a Voc of 0.66 V is obtained. Clearly, a-Si:H(i/p) contributes a stronger back-surface field than Al, without introducing problems in current collection. On planar 2.0 Ω·cm n-type FZ-Si, we obtain an even higher Voc of 0.69 V. Of particular importance is that Voc does not suffer from using a textured surface compared to a planar substrate. Using a textured bare FZ-Si wafer, we obtain a confirmed efficiency of 17.5% (see Figure 2), the highest reported for a p-type c-Si based heterojunction solar cell.

3 Conclusions

Effective a-Si:H/c-Si heterointerfaces with minimal recombination loss can be obtained using HWCVD. Abrupt a-Si:H(i) deposition and a flat hetero-interface to the c-Si substrate achieved at low-temperature (<150°C) ensures that the a-Si:H contacts high quality c-Si with low interface defect density and high band bending while minimizing the a-Si:H/c-Si interface area. A higher temperature (~200°C) deposition of the subsequent doped layer enhances the interface passivation and the built-in voltage, likely by activating dopants and reducing defect density in both the underlying i- and the doped-layer. When HWCVD a-Si:H is used as the back collector, a highly effective back-surface field is demonstrated by double-heterojunction SHJ devices with preliminary Voc values of 691 mV and 660 mV on planar n-type FZ-Si and on textured p-type FZ-Si, respectively.

Fig. 2. IV-curve of the 1-cm² double-heterojunction cell.

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REFERENCES


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