Junction Transport in Epitaxial Film Silicon Heterojunction Solar Cells

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David L. Young, Jian V. Li, Charles W. Teplin, Paul Stradins, and Howard M. Branz

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JUNCTION TRANSPORT IN EPITAXIAL FILM SILICON HETEROJUNCTION SOLAR CELLS

David L. Young, Jian V. Li, Charles W. Teplin, Paul Stradins, and Howard M. Branz
National Renewable Energy Laboratory, Golden, CO USA

ABSTRACT

We report our progress toward low-temperature HWCVD epitaxial film silicon solar cells on inexpensive seed layers, with a focus on the junction transport physics exhibited by our devices. Heterojunctions of i/p hydrogenated amorphous Si (a-Si) on our n-type epitaxial crystal Si on n++ Si wafers show space-charge-region recombination, tunneling or diffusive transport depending on both epitaxial Si quality and the applied forward voltage.

INTRODUCTION

Today’s commercial photovoltaic market is dominated by crystalline silicon wafer technology, however an increasing share of the market is shifting toward thin-film materials due to cost advantages in fabricating large area semiconductors. Many research groups are working on crystalline film-silicon (1-40 µm) solar cells to take advantage of the potential cost advantage, high efficiency, scientific knowledge base and marketplace inertia toward silicon-based semiconductors. Our group has been developing a low-cost hot wire chemical vapor (HWCVD) epitaxial growth technique to form high efficiency epitaxial film silicon solar cells at temperatures between 620 and 830°C on inexpensive substrates coated in crystalline seed layers. Our 2-µm-thick devices grown on heavily doped wafers have shown Voc values as high as 630 mV with fill factors of 78%. Devices grown on seed layers (both hetero- and homo-epitaxy) with no Si wafer exhibit device parameters that exceed those of fine-grained polysilicon devices on display glass.

These high voltages indicate high quality epitaxial material with effective minority carrier diffusion length, L_eff, more than 3 times the absorber thickness. However, our epitaxial films have threading dislocation densities in the 10^5 – 10^6 cm^-2 range (imaged by electron-beam induced current) and crystalline pit and tower structures on the surface of the films at densities <10^5 cm^-2 (imaged by scanning electron microscopy). The effect of these electronic and crystallographic structures can be significant and yet the high Voc values our a-Si/c-Si heterojunction cells demand a closer look and analysis. The question addressed here is whether devices made from our low-temperature epitaxial films, despite the dislocation, pits and towers, can operate with similar transport physics as wafer-based heterojunction devices. In other words, can our films form electronically clean enough interfaces and provide long enough bulk minority carrier lifetimes to allow tunneling and diffusive transport across the interface rather than voltage-killing recombination in the bulk.

In this contribution, we will compare the device physics of our heterojunction solar cells with that of wafer-based a-Si/c-Si heterojunction solar cells. Our study relies on analysis of temperature dependent dark current density vs voltage (JV(T)) measurements. The transport mechanisms measured in our best film-silicon devices are similar to those of the wafer-based a-Si/c-Si heterojunction solar cells, but further improvement of the Si epitaxy is needed to improve Voc values to the 650 mV range.

EXPERIMENT

Epitaxial films are grown by HWCVD using a gas mixture of SiH₄, H₂, and PH₃ over a temperature range from 650 to 830°C. Details of the film growth can be found elsewhere. Films are grown on either heavily doped (2x10¹⁹ cm⁻³), RCA cleaned, Si:As wafers or on a variety of substrates coated with proprietary seed layers to promote epitaxial silicon growth. Seed substrates are glass, ceramic or metal foils. Heterojunction formation (~5 nm of intrinsic a-Si followed by ~15 nm of p-type a-Si:B) is done in a separate HWCVD deposition chamber after a 4% HF etch. Next, a 700 nm thick layer of In₂O₃:Sn is deposited by reactive evaporation to provide a transparent conducting layer and a top contact. Small area (0.05 cm²) round mesa devices are isolated by wet and dry chemical techniques. Back contacts are formed either to the highly conducting wafer or to a grown-in, heavily doped back surface field layer (See reference [7] for details).

<table>
<thead>
<tr>
<th>Epi/a-Si Device</th>
<th>Voc (mV)</th>
<th>Jsc (mA/cm²)</th>
<th>FF (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(No light trapping)</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>627</td>
<td>12.43</td>
<td>74.98</td>
</tr>
<tr>
<td>2</td>
<td>600</td>
<td>14.1</td>
<td>75.4</td>
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<tr>
<td>3</td>
<td>570</td>
<td>15.3</td>
<td>72.5</td>
</tr>
<tr>
<td>4</td>
<td>555</td>
<td>17.7</td>
<td>68.6</td>
</tr>
<tr>
<td>5</td>
<td>555</td>
<td>11.7</td>
<td>67.2</td>
</tr>
</tbody>
</table>

Table 1, Device parameters.

Measurements of light current density vs voltage are done with a calibrated AM1.5 solar simulator to give device operating parameters. JV(T) measurements are made between 77 K – 350 K, at ~10°C steps, with a Linkam Scientific cryostat and a Keithley 6517B electrometer. DLTS measurements are made with custom equipment.
RESULTS AND DISCUSSION

Samples of different quality were selected for this study to determine the main junction transport mechanism responsible for limiting \( V_{oc} \) in our films. Table 1 shows device parameters for these samples. Note that devices 1-4 have \( V_{oc} \) ranging from 555 to 627 mV while the difference between devices 4 and 5 is the \( J_{sc} \) value.

Device 1 reached the highest \( V_{oc} \) through a hydrogen passivation treatment that will be described elsewhere. Here, we will show detailed data for Device 2, with \( V_{oc} \equiv 600 \) mV, and compare them to key results and conclusions for the other devices. Figure 1 shows dark JV(T) data for Device 2 over the temperature range of 250 – 350 K and voltage range of -2 to 1.2 Volts.

The forward bias data of Fig. 1 can be fit with a simplified diode relationship

\[
J = J_o \exp[AV]
\]

where

\[
A = \frac{q}{nkT}
\]

for both diffusion and space-charge-region recombination (SCRR) models. Here, \( k \) is Boltzmann’s constant, \( T \) is the measurement temperature, \( n \) is the diode ideality factor and \( q \) is the elementary charge. However, if transport is instead governed by tunneling, \( A \) becomes a temperature-independent constant. The pre-exponential factor \( J_o \) can be described by

\[
J_o \propto \exp\left(-\frac{\Delta E_a}{kT}\right)
\]

where \( \Delta E_a \) is an activation energy associated with the rate limiting recombination process [14]. Analysis of the forward bias data in Fig. 1 reveals four voltage regions characterized by a significant change in slope (different \( A \) values in Eq. 1) or some curvature. These regions, identified in Figure 2, each indicate a change in transport mechanism. A 2-parameter fit of the forward bias data of Fig. 2 to Eq. 1 gives the temperature dependence of the \( A \) factor (see Fig. 3) and \( J_o \) (see Fig. 4) in voltage regions 1-3. In contrast, region 4 shows the \( J \sim V^2 \) dependence characteristic of space-charge-limited transport in high forward bias [15].

Fig. 3 clearly shows that \( A \) depends strongly on \( T \) in regions 1 - 2 but is nearly \( T \)-independent in Region 3. In regions 1 and 2, Eqn. (2) yields \( n \) values above 2, consistent with a space-charge-region recombination (SCRR) mechanism [16]. In Region 3, the \( A \) factor is
nearly constant over the temperature range measured indicating tunneling transport as the rate limiting step [15].

Figure 4 shows $\ln(J_0)$ vs. $1/kT$, that we use to find the slope $E_a$, which is the transport activation energy according to Eq. (3). Bias regions 1 and 2 give lower $E_a$ values (0.19 eV and 0.14 eV, respectively), while $E_a$ in region 3 is much higher at 0.37 eV. The lack of $T$-dependence of $A$ in Region 3 is consistent with the multitunneling capture-emission model of Matsuura et al [14]. The activation energy of $J_0$ in Region 3 is consistent with the conductivity activation energy in the doped p-type a-Si:B layer (~ 0.4 eV) as noted elsewhere [12, 14].

From the data of Figures 1- 4, it is clear that the operating transport mechanism within Device 2 shifts with increasing forward bias from an SCRR capture/emission process to/from increasing shallow defects, followed by an abrupt change to tunneling-like behavior as the forward bias approaches $V_{oc}$. The $E_a \sim 0.4$ value of $J_0$ in the tunneling region suggests [12] that the dominate dark current arises from an electron in the conduction band of the n-type epi c-Si tunneling through states in the i-a-Si layer, separated by energy $< kT$, to recombine with a hole from the a-Si:B layer. The hole transport through the p-layer is presumably the rate-limiting step.

Similar analysis of dark $JV(T)$ data were completed for devices 1-5. The results from these devices are shown in Table 2. At low bias (typically less than 0.4 V) the lower-voltage devices 3 and 4 show tunneling behavior with similar $E_a$ values to that of Device 2. However, at high bias (greater than 0.4 V) the $A$ value in Eq. 1 becomes temperature dependent with an $n$ value greater than 2 and an $E_a$ value around 0.5 eV. These data indicate SCR recombination to a mid-gap level in the c-Si epitaxy layer near the operating voltage of the device. The worst-performing Device 5 showed SCR recombination with $E_a \sim 0.3$ eV across all forward biases. No tunneling-like transport was observed for this sample. It should be noted that device 5 showed a mid-gap minority carrier trap by DLTS. The origin of this trap is not yet known.

Device 1, with the highest $V_{oc}$ of 627 mV, has very different transport behavior with increasing forward bias compared to the other epi/a-Si devices. At low bias, it shows tunneling transport with an activation energy of 0.34 eV. As forward bias increases, however, the $A$ value becomes temperature dependent with an activation energy for $J_0$ of 0.92 eV and an $n$ values less than 2. These values point toward diffusive transport of electrons over the heterojunction barrier rather than tunneling or SCR in the base.

For perspective on the data of Table 2 we compare our data to a wafer-based heterojunction solar cell with $V_{oc} > 710$ mV fabricated by Sanyo [12]. From Table 2, we see that at low bias, the Sanyo HIT cell exhibits tunneling transport with an $E_a$ of 0.41 eV. However, above about 0.4 V forward bias the Sanyo device switches to diffusive transport ($n=1.2$) with an $E_a$ of 1.13 eV – the bandgap of the c-Si wafer absorber layer. This very significant change – apparently an optimized transport mechanism, allows the Sanyo device to have record high $V_{oc}$ values. The Sanyo HIT cell acts like a diffused junction device near the maximum power point, but benefits from the band offsets between crystal and amorphous Si to increase $V_{oc}$.

Our epi/a-Si Device 1 shares the Sanyo cell’s transport regimes despite having dislocations and crystallographic defects. From Table 2 we see that increasing $V_{oc}$ in our devices is accompanied by a dark current transport mechanism shift from SCR recombination to tunneling and finally to diffusion over the junction barriers. The particular transport reveals much about the bulk and surface quality. Device 2 is limited by tunneling at the interface, however, Device 1 reached diffusive transport by the addition of a hydrogen passivation processing step that also increased the voltage.
CONCLUSION

Our study of c-Si/a-Si junction physics on low-temperature, HWCVD epitaxial films by dark JV(T) data indicate that space-charge-region recombination and tunneling are the main transport mechanisms operating in devices with V_{oc} < 600 mV. Devices that are hydrogen passivated prior to growth of the c-Si/a-Si heterojunction show diffusive transport over the junction barrier which allows V_{oc} values as high as 630 mV.

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