Silicon heterojunction solar cell characterization and optimization using *in situ* and *ex situ* spectroscopic ellipsometry

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SHJ Solar Cell Fabrication

0 - n-type c-Si

3 - HWCVD p-layer 60Å
2 – HWCVD i-layer 40Å

5 – HWCVD i-layer 40Å
6 – HWCVD n-layer 60Å

7 - ITO
8 - ITO
9 - Back Contact

10 - Front Contact
11 - Photolithography/mesa etch

1 - cleaned by 2.5% HF

4 - cleaned by 2.5% HF

Ellipsometry studies

Flat wafers  \( \eta = 16.9\% \)
Textured wafers  \( \eta = 17.8\% \)
HWCVD deposition system:
i, n, and p layers are deposited in separate chambers

ellipsometer

n layer

i layer

p layer
Fabrication and characterization sequence

- **in situ RTSE**
  - Measures individual layers during deposition
  - layer thickness
  - growth rate
  - surface roughness
  - optical properties
  - crystallinity

- **ex situ VASE**
  - Measures all layers at once in completed device

**RTSE**

<table>
<thead>
<tr>
<th>c-Si wafer</th>
<th>etch</th>
</tr>
</thead>
<tbody>
<tr>
<td>i-layer - front</td>
<td>vacuum</td>
</tr>
<tr>
<td>p-layer - front</td>
<td>etch</td>
</tr>
<tr>
<td>i-layer - back</td>
<td>air break</td>
</tr>
<tr>
<td>n-layer - back</td>
<td>air break</td>
</tr>
<tr>
<td>ITO deposition 2x</td>
<td></td>
</tr>
<tr>
<td>Metalization 2x</td>
<td></td>
</tr>
<tr>
<td>Mesa etching &amp; isolation</td>
<td></td>
</tr>
<tr>
<td>PV device testing</td>
<td></td>
</tr>
</tbody>
</table>
in situ ellipsometry of a-Si:H growth

- Surface roughness indicates growth dynamics
- Optical properties reveal structural and electronic properties
Evolution of surface roughness: $R_s$

- The evolution of $R_s$ with bulk film thickness $d_b$ provides insight into the film growth process.
- $R_s$ can be represented as a function of $d_b$

\[ R_s \propto d^\beta \]

Growth exponent $\beta$

Universality classes

- $\beta = 0.5$ random deposition
- $\beta = 0.25$ RD w/diffusion
- $\beta = 0$ RD w/relaxation

\[ T_s = 75^\circ C \]

$\beta = 0.31$
Growth exponent for i-layer growth

- \( \beta \) is nearly constant for \( T_s < 145^\circ C \)
- Abrupt increase in \( \beta \) above 145\(^o\)C indicates change in growth mode – uc-Si deposition
Optical properties vs $T_s$

- i layers are deposited on oxide-free <100> c-Si etched in 5% HF

- 73C – 126C layers all a-Si:H
- 144C layer is mixed a-Si:H uc-Si:H
- 162C layer is epitaxial c-Si
Analysis of i-layer $\varepsilon_2$ $T_s$ dependence

\[
\frac{d\varepsilon_2}{dT_s} = -210 \text{ meV/100}^\circ\text{C}
\]
\[
\frac{dE_g}{dT_s} = -60 \text{ meV/100}^\circ\text{C}
\]

$\Delta\frac{d(\varepsilon_2/dT_s)}{dT_s} = 17 \text{ meV / 1 at.\% C(H)}^*$

12% drop in C(H) w/100$^\circ$C increase in $T_s$

ex situ ellipsometry of finished devices

- Ellipsometry measurement and analysis
- Optical model to calculate R, T, A for each layer
- Compare calculations with device performance
  - SHJ compared w/diffused junction
  - 2 SHJ devices w/different p-doping
**ex situ** SE on finished devices

**Example:** single-sided n-i-p SHJ

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface roughness</td>
<td>65 Å</td>
</tr>
<tr>
<td>ITO</td>
<td>835 Å</td>
</tr>
<tr>
<td>n layer</td>
<td>57 Å</td>
</tr>
<tr>
<td>i layer (100°C)</td>
<td>40 Å</td>
</tr>
<tr>
<td>c-Si (p-type)</td>
<td>200 μm</td>
</tr>
</tbody>
</table>

SE measures the amplitude ratio $\Psi$ and the phase change $\Delta$ as a function of wavelength at multiple angles.

$$\Psi(\lambda), \Delta(\lambda) = f[ n_i(\lambda), k_i(\lambda), d_i ]$$

Least squares.
Comparison of SHJ w/diffused junction cell

- Two devices are identical except for front junction (both use Al-BSF contact)
**ex situ SE:** p-doping comparison

- 2 nominally identical devices
- 2 sccm vs 18 sccm B$_2$H$_6$

### Deposition

<table>
<thead>
<tr>
<th>Time</th>
<th>Deposition</th>
<th>Absorption (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 sec</td>
<td>2 sccm</td>
<td></td>
</tr>
<tr>
<td>9 sec</td>
<td>18 sccm</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Surface roughness</th>
<th>56 Å</th>
</tr>
</thead>
<tbody>
<tr>
<td>ITO</td>
<td>752 Å</td>
</tr>
<tr>
<td>p layer (2 sccm B$_2$H$_6$)</td>
<td>118 Å</td>
</tr>
<tr>
<td>i layer (100°C)</td>
<td>35 Å</td>
</tr>
<tr>
<td>c-Si</td>
<td>200 μm</td>
</tr>
</tbody>
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<td>18 sccm</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Surface roughness</th>
<th>142 Å</th>
</tr>
</thead>
<tbody>
<tr>
<td>ITO</td>
<td>766 Å</td>
</tr>
<tr>
<td>p layer (18 sccm B$_2$H$_6$)</td>
<td>96 Å</td>
</tr>
<tr>
<td>i layer (100°C)</td>
<td>35 Å</td>
</tr>
<tr>
<td>c-Si</td>
<td>200 μm</td>
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</table>
Device optical performance comparison

- Layer thicknesses and optical constants determined by *ex situ* SE
- Primary difference is p layer doping – flow rate of B₂H₆
- Optical model enables calculation of contribution of each layer

% spectral loss:
18 sccm vs. 2 sccm device = 4.4%

<table>
<thead>
<tr>
<th>component</th>
<th>% contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>p-layer abs</td>
<td>38</td>
</tr>
<tr>
<td>i-layer abs</td>
<td>14</td>
</tr>
<tr>
<td>reflection</td>
<td>34</td>
</tr>
<tr>
<td>ITO abs</td>
<td>14</td>
</tr>
</tbody>
</table>
Summary

• *in situ* SE gives insight into growth mechanisms and accurate layer thickness

• *ex situ* SE measures completed device structures to determine integrated optical properties

• The combination of *in situ* and *ex situ* SE provides a powerful method for pinpointing the effects of processing changes in actual SHJ devices and guiding optimization.
Acknowledgements

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