Faculty of Engineering
School of Photovoltaic and Renewable Energy Engineering

Optical Optimization for III-V//Si Multijunction Solar cells

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Background

Transparent conductive adhesives (TCA) layer for 2-terminal III-V//Si multijunction solar cells
- Optical transparency
- Electrical conductivity

Optical optimization of 4-terminal III-V//Si multijunction solar cells
- Photon recycling to further improve performance
- Optical transparency of long wavelength photons
Background

- **Multijunction solar cell: broader solar spectrum**

- **Why chose III-V and Silicon**
  - Si: low cost/mature industrial technology---but reaching efficiency limit
  - III-V tandem: highest efficiency---but high cost
  - III-V/Si tandem: high efficiency & low cost

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Background

The approaches to obtain III-V/Si tandem solar cell:

- Epitaxy growth
- Non-epitaxy growth:
  - 2-terminal via bonding
  - 4-terminal mechanically stacking

The advantages of Non-epitaxy route:

- Lattice-mismatched subcells
- Individual process for each cell
- Current matching can be ignored in 4 terminals

2-Terminal and 4-Terminal III-V//Si multijunction solar cells

# Background

## Current status in III-V//Si multi-junction solar cells

<table>
<thead>
<tr>
<th>Structure</th>
<th>Top cell efficiency</th>
<th>Bottom cell efficiency</th>
<th>Total efficiency</th>
<th>Boding method</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>4T</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GaInP//Si</td>
<td>20%</td>
<td>13.26%</td>
<td>32.45%</td>
<td>Epoxy + glass¹</td>
</tr>
<tr>
<td>GaAs//Si</td>
<td>26.8%</td>
<td>9.68%</td>
<td>32.82%</td>
<td></td>
</tr>
<tr>
<td>GaInP/GaAs//Si</td>
<td>30.01%</td>
<td>7.27%</td>
<td>35.91%</td>
<td></td>
</tr>
<tr>
<td><strong>2T</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GaInP/GaAs//Si</td>
<td>N/A</td>
<td></td>
<td>30.93%</td>
<td>Epoxy + glass¹</td>
</tr>
<tr>
<td>InGaP/GaAs//Si</td>
<td>N/A</td>
<td></td>
<td>25.10%</td>
<td>Pd array²</td>
</tr>
<tr>
<td>GaInP/InGaAs//Si</td>
<td>N/A</td>
<td></td>
<td>25.5%</td>
<td>Ti /Pt/Au³</td>
</tr>
<tr>
<td>GaInP/GaAs//Si</td>
<td>N/A</td>
<td></td>
<td>33.3%</td>
<td>Surface-activated wafer bonding⁴</td>
</tr>
</tbody>
</table>

## Proper TCA layer required for 2-Terminal III-V//Si multijunction solar cells

- Optical losses for bottom cell
- Electrical losses introduced by intermediate layer

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TCA for 2-terminal III-V//Si multijunction solar cells

**TCA fabrication process:**

I. Prepare Epoxy and metal particles/wires mixture.
II. Uniform coverage on the bottom cell surface.
III. Cover with top cell before curing the adhesive.

**Optical/electrical measurement:**

- Resistance measurement: 4-point
- Optical measurement: sample without Al contact as reference
Transmission measurements with varying microsphere density show reduced transmission with increasing percent area coverages of microspheres in long wavelength (900~1200nm).
The linear relationship between microsphere density, coverage and transmission

- The relationship between T, A and d are got to further analysis performance of this TCA on multijunction solar cell:

\[ T = -0.7749 \times A + 88.451 \quad (R^2 = 0.9547) \]

\[ A = 0.0957 \times d + 0.2718 \quad (R^2 = 0.9594) \]
**Electrical characteristic and optimum parameters**

\[
R = \frac{\rho l}{S_mA} = \frac{k_1}{S_mA}
\]

- **R**: Resistance measured
- **\(S_m\)**: contact area
- **A**: percent area coverages of microspheres

\[R\text{ and } A \cdot S_m\text{ are reciprocal relations.}\]

\[k_1 \approx 1\]

\[T = T_{max} - k_2 A \quad T_{max} = 0.88, k_2 \approx 0.75\]

After considering the trade-off between optical and electrical property, the optimal area coverage of microsphere is obtained:

\[A^{optimum} = 5.6\% \quad (V_{oc} = 3.2V, I = 0.01A/cm^2)\]
Optical optimization of 4-terminal III-V//Si multijunction solar cells

- Photon recycling in 4-Terminals III-V//Si multijunction solar cell

Photon recycling in single junction III-V solar cell

- **Main losses:**
  - Top cell: efficiency is ~2% lower compared with metal back single cell
    - Photon recycling required
  - Optical losses introduced by intermediate layer
    - Long wavelength transmission required

Optical optimization of 4-terminal III-V//Si multijunction solar cells

## Basic structures

<table>
<thead>
<tr>
<th>Epoxy</th>
<th>Epoxy + Metal</th>
<th>Epoxy + Si_disc</th>
<th>Epoxy + holes</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaAs/epoxy/Si</td>
<td>GaAs/epoxy/Ag/Si</td>
<td>GaAs/epoxy/Si_disc/Si</td>
<td>GaAs/epoxy/holes/Si</td>
</tr>
</tbody>
</table>

* The model represents the simplified structure of tandem solar cells.*
Optical optimization of 4-terminal III-V//Si multijunction solar cells

Silicon disc
Nano imprinting technology

Ag
h=50 nm
w=180 nm
p=220 nm

TiO₂ holes
h=30~50 nm
R=60-90 nm
P~2*R

Silicon holes
h=50 nm
r=80 nm
P~2*r
### I. Ag and Silicon disc

\[ J_{sc} = Q \times \int \Phi(\lambda) \times \text{abs} \times \frac{1}{\Delta \lambda} d(\lambda) \]

<table>
<thead>
<tr>
<th>NO.</th>
<th>Jsc_top</th>
<th>Jsc_bottom</th>
<th>Jsc_total</th>
<th>parameters</th>
<th>Enhancement factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>28.59</td>
<td>13.50</td>
<td>42.09</td>
<td>GaAs/epoxy/Si</td>
<td>reference</td>
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<tr>
<td>9</td>
<td>29.82</td>
<td>13.53</td>
<td>43.35</td>
<td>Ag</td>
<td>1.26</td>
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<tr>
<td>19</td>
<td>28.83</td>
<td>14.30</td>
<td>43.12</td>
<td>Si_disc:h30_r40_p180</td>
<td>1.03</td>
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<tr>
<td>103</td>
<td>29.73</td>
<td>13.31</td>
<td>43.04</td>
<td>9+19</td>
<td>0.95</td>
</tr>
</tbody>
</table>

### II. Silicon Holes array

<table>
<thead>
<tr>
<th>NO.</th>
<th>Jsc_top</th>
<th>Jsc_bottom</th>
<th>Jsc_total</th>
<th>parameters</th>
<th>Enhancement factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>35</td>
<td>28.71</td>
<td>14.25</td>
<td>42.96</td>
<td>Si_holes: h=30 r=80 p=180</td>
<td>0.87</td>
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<tr>
<td>36</td>
<td>28.68</td>
<td>14.42</td>
<td>43.10</td>
<td>Si_holes: h=50 r=80 p=180</td>
<td>1.01</td>
</tr>
<tr>
<td>37</td>
<td>28.57</td>
<td>14.22</td>
<td>42.79</td>
<td>Si_holes: h=70 r=80 p=180</td>
<td>0.70</td>
</tr>
</tbody>
</table>

### III. TiO₂ Holes array

<table>
<thead>
<tr>
<th>NO.</th>
<th>Jsc_top</th>
<th>Jsc_bottom</th>
<th>Jsc_total</th>
<th>parameters</th>
<th>Enhancement factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>34</td>
<td>28.83</td>
<td>14.31</td>
<td>43.14</td>
<td>TiO2_holes (h=30 r=80 p=180)</td>
<td>1.05</td>
</tr>
<tr>
<td>38</td>
<td>28.92</td>
<td>14.29</td>
<td>43.20</td>
<td>TiO2_holes (h=50 r=80 p=180)</td>
<td>1.11</td>
</tr>
<tr>
<td>40</td>
<td>28.91</td>
<td>14.29</td>
<td>43.20</td>
<td>TiO2_holes (h=50 r=89 p=200)</td>
<td>1.11</td>
</tr>
<tr>
<td>41</td>
<td>28.92</td>
<td>14.29</td>
<td>43.21</td>
<td>TiO2_holes (h=50 r=71 p=160)</td>
<td>1.12</td>
</tr>
<tr>
<td>42</td>
<td>28.93</td>
<td>14.29</td>
<td>43.21</td>
<td>TiO2_holes (h=50 r=67 p=150)</td>
<td>1.12</td>
</tr>
</tbody>
</table>
Summary

➢ **TCA layer for 2 terminals III-V//Si multijunction solar cells**
  • Relationship obtained between microsphere density, coverage percent, transmission and Resistance
  • Optimized density of microsphere for high efficiency III-V//Si multijunction solar cell

➢ **Intermediate layer design to get high efficiency in 4 terminals III-V//Si multijunction solar cells**
  • Ag nanostructure, Silicon disc and TiO$_2$ hole array show evident improvement in top cell or bottom cell
Thanks for your attention