Monolithic, Ultra-Thin GaInP/GaAs/GaInAs Tandem Solar Cells

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Monolithic, Ultra-Thin GaInP/GaAs/GaInAs Tandem Solar Cells

- NREL IR # 05-05, patent pending.
- Near-optimum subcell bandgaps.
- ~300 mV voltage output boost compared to conventional Ge-based triple-junction tandems.
- Bottom subcell $E_g$ is variable.
- Basic approach is expandable to 4-6 subcells.

GaInP: Top subcell absorber, transparent GL, MCC for GaInAs.

~1-eV GaInAs

Top

Middle

Bottom

~1-eV GaInAsN

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Inverted GaInP/GaAs/GaInAs Tandem Structure

- GaAs substrate
- n+-GaInP etch stop
- n+-GaAs contact
- p+/n+-GaAs tunnel junction
- n/p GaAs/GaInP DH
- p*/n*-GaAs tunnel junction
- Compositionally step-graded n-GaInP
- p*-GaInAs contact
- 1.4-eV Middle Subcell
- 1.9-eV Top Subcell
- Transparent Graded Layer
- n/p GaAs/GaInP DH
- p*/n*-GaAs tunnel junction
- n/p GaInP/AlInP DH
- n*-GaAs contact
- n*-GaInP etch stop
- GaAs substrate
- Solar radiation

Back surface: Handle mount, back contact, BSR.
**Ultra-thin Tandem Cell Processing Sequence**

1) Inverted tandem structure is grown on the parent substrate, and the back contact/BSR is formed.

2) Epistucture is mounted upside down on a handle material (secondary support substrate).

3) Parent substrate is removed.

4) Front-surface processing is completed.
Advantages of Ultra-Thin, Handle-Mounted Tandem Solar Cells

• Handle material can be engineered to have a wide range of advantageous characteristics.
• Thermal management can be optimized.
• Highest specific power (W/kg) for space applications.
• Reuse and/or reclamation of the parent substrate also possible, reducing cost.
• Parent substrate can be impure to reduce cost.
• Benefits of BSR: thin GaInAs subcell, lower J₀, improved radiation hardness, reduced operating temperature.
Semi-Realistic Performance Modeling GaInP/GaAs/GaInAs

Low-AOD Direct Spectrum, 250 suns, 25°C
QE = 0.95, realistic $J_0(E_g)$, no parasitic losses

Subcell parameters

<table>
<thead>
<tr>
<th>Subcell Absorber</th>
<th>$E_g$ (eV)</th>
<th>$V_{oc}$ (V)</th>
<th>$J_{sc}$ (A/cm²)</th>
<th>FF (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaInP</td>
<td>1.87</td>
<td>1.53</td>
<td>3.40</td>
<td>91.57</td>
</tr>
<tr>
<td>GaAs</td>
<td>1.42</td>
<td>1.12</td>
<td>3.40</td>
<td>89.23</td>
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<tr>
<td>GaInAs</td>
<td>1.01</td>
<td>0.74</td>
<td>3.63</td>
<td>85.21</td>
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</tbody>
</table>

Series-connected tandem parameters

<table>
<thead>
<tr>
<th>$V_{oc}$ (V)</th>
<th>$J_{sc}$ (A/cm²)</th>
<th>FF (%)</th>
<th>$V_{max}$ (V)</th>
<th>$J_{max}$ (A/cm²)</th>
<th>$P_{max}$ (W/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.38</td>
<td>3.40</td>
<td>90.32</td>
<td>3.11</td>
<td>3.34</td>
<td>10.38</td>
</tr>
</tbody>
</table>

Tandem efficiency: 41.5%
Semi-Realistic Performance Modeling

**Conditions**
- AM0, one sun, 25°C
- QE = 0.95, Realistic $J_0(E_g)$

**Tandem efficiency**
- ~33% (one sun)
- ~36% (10 suns)

### Subcell parameters

<table>
<thead>
<tr>
<th>Subcell Absorber</th>
<th>$E_g$ (eV)</th>
<th>$V_{oc}$ (V)</th>
<th>$J_{sc}$ (mA/cm²)</th>
<th>FF (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaInP</td>
<td>1.87</td>
<td>1.393</td>
<td>17.00</td>
<td>90.94</td>
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<tr>
<td>GaAs</td>
<td>1.42</td>
<td>0.981</td>
<td>17.00</td>
<td>88.09</td>
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<tr>
<td>GaInAs</td>
<td>1.02</td>
<td>0.608</td>
<td>18.13</td>
<td>83.01</td>
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</table>

### Series-connected tandem parameters

<table>
<thead>
<tr>
<th>$V_{oc}$ (V)</th>
<th>$J_{sc}$ (mA/cm²)</th>
<th>FF (%)</th>
<th>$V_{max}$ (V)</th>
<th>$J_{max}$ (mA/cm²)</th>
<th>$P_{max}$ (mW/cm²)</th>
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</thead>
<tbody>
<tr>
<td>2.98</td>
<td>17.00</td>
<td>89.27</td>
<td>2.72</td>
<td>16.65</td>
<td>45.26</td>
</tr>
</tbody>
</table>
Defects in LMM, ~1-eV GaInAs

XTEM

Plan-view CL

Grid line

TD density ~ 2E6 cm$^{-2}$
~1-eV, LMM (2.2%) GaInAs/GaInP DH Cell Performance

Internal Quantum Efficiency

Current (Voltage)

Single-junction GaInAs
Low AOD @ one sun
Voc = 0.56V
Jsc = 18.6 mA/cm²
FF = 75%
Ultra-Thin, Handle-Mounted GaInP/GaAs/GaInAsTandem AEQE & R Data

- QE is excellent for all subcells, but some improvement is still possible (reduce parasitic absorption and reflection).
- ZnS/MgF$_2$ ARC is not optimal.
- Interference evident in thin bottom subcell.
## Reported Performance

<table>
<thead>
<tr>
<th>Facility</th>
<th>Date</th>
<th>Conditions</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>PVSC</td>
<td>1/3-7/05</td>
<td>Global, 25°C</td>
<td>31.1%</td>
</tr>
<tr>
<td>SPW</td>
<td>4/18-21/05</td>
<td>AM0, 1 sun, 25°C</td>
<td>29.7%</td>
</tr>
<tr>
<td>ISCC</td>
<td>5/1-5/05</td>
<td>Direct, 10.1 suns, 25°C</td>
<td>37.9%</td>
</tr>
<tr>
<td>SPRAT</td>
<td>9/20-22/05</td>
<td>AM0, 1 sun, 25°C Kapton handle</td>
<td>26.5%</td>
</tr>
<tr>
<td>SPRAT</td>
<td>9/20-22/05</td>
<td>AM0, 8.9 suns, 25°C</td>
<td>31.4%</td>
</tr>
</tbody>
</table>
$V_{oc}$, FF (Concentration Ratio)

- $<n> = 1.36$
- $<n> = 0.92$

Concentration with water filtered 1 kW Xe lamp and fast V for temperature

MF602 #2, GaInP/GaAs/GaInAs
Cell temperature = 25 °C
High-performance, low-AOD AM1.5 direct
Area = 0.2428 cm$^2$
I-V Data at Peak Efficiency

- $\eta = 37.9\%$ (10.1 suns).

- On 4/25/05, a new record for solar PV conversion.

- With continued development, $\eta > 40\%$ possible at higher concentration ratios.
Recent progress

$V_{oc}$ and FF vs $I_{sc}$

Sample ID: NRE MG468#7

April 11, 2006

~200 suns
Research Issues

• High-yield processing of handle-mounted, ultra-thin devices.

• Develop process enabling reuse of parent substrate.

• Tandem cell efficiency testing more difficult w/ 1-eV subcell - even more difficult as we consider more than three subcells.

• Inverted tunnel junctions.

• Radiation effects.

• Push efficiency limits by including more subcells - can we achieve 40-50% (terr. conc.), 35-40% (AM0)?
Advanced Design Options

- Concept applies to two, or more, subcells.
- A wide range of substrates, subcell materials, tunnel junction materials, and transparent compositional grades are possible.
- Substrates: GaAs, Ge, Si, SiGe.
- Subcells, etc.: AlGaInPAsSb.

Legend:
LM = lattice matched.
LMM = lattice mismatched.
DH = double heterostructure.