Multijunction GaInP/GaAs Solar Cells Grown by Hydride Vapor Phase Epitaxy

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Reduction the Cost

Hydride Vapor Phase Epitaxy (HVPE)

HVPE advantages:
- Low cost precursors
- Proven high deposition rate (~300 μm/h for GaAs)
- High material utilization (V/III < 4, potential metals recycling & lower grade metals)
But:
- Applications limited to bulk applications due to difficulty forming hetero-interfaces
Pushing the Limits

Traditional HVPE Products

GaN Substrates

GaN

Sapphire Substrate

Visible LEDs

diffused Zn junction

n-GaAs$_x$P$_{1-x}$

n-GaAs$_x$P$_{1-x}$ Grade

n-GaAs Substrate

Inverted Tandem GaInP/GaAs Cell

p$^+$-GaInP BSF

n-GaAs base

n$^+$-GaInP window

n$^{++}$-GaAs TJ layer

p$^+$-GaInP BSF

p-GaInP base

n-GaInP emitter

n$^+$-GaAs Contact

n-GaInP etch stop

n-GaAs Buffer

n-GaAs Substrate

3 doping type switches  7 hetero-interfaces

Dynamic HVPE

1. Heat substrate/remove oxide
2. Nucleate p-GaAs buffer
3. n-GaInP Window
4. n-GaAs base layer
5. p-GaInP emitter layer
6. p+-GaAs contact layer
7. Remove from system

Inverted rear heterojunction GaAs cell

Simulates possible industrial in-line process
Tandem Component Development

ARC-coated GaInP Cell

- HC017
- $V_{OC} (V) = 1.41$
- $W_{OC} (V) = 0.47$
- $J_{SC} (mA/cm^2) = 11.4$
- FF (%) = 85.8
- Eff (%) = 13.8

Current Density (mA/cm$^2$) vs. Voltage (V)

1. GaInP top cell
2. TJ
3. GaAs bottom cell

GaInP base
GaInP emitter
GaInP back surface field
GaAs contact layer
GaAs base
GaInP window
Back Au metal
ZnS/MgF$_2$
ARC
Au top contact
Tunnel junction interconnect

Graph showing the current density and voltage characteristics of the GaInP cell with ARC coating.
Tandem Component Development

![Tandem Component Diagram]

1. GaInP top cell
2. TJ
3. GaAs bottom cell

**Tunnel Junction**

730 suns

- Current Density (A/cm²)
- Voltage (V)

Insert graph showing current density and voltage for GaInP and GaAs layers.

- p-GaInP ~4x10¹⁶ cm⁻³
- n-GaAs ~2x10¹⁹ cm⁻³

HC303
Tandem Component Development

- ARC-coated GaAs Cell
  - HVPE (HC235) $V_{OC} = 1.08$ V
  - MOVPE (MP039) $V_{OC} = 1.10$ V

Graph showing current density versus voltage:
- HVPE Growth Rate: 1.0 µm/min
- MOVPE Growth Rate: 0.1 µm/min
Putting it All Together

GaInP Base: 0.9 µm/min
GaAs Base: 1.0 µm/min

$T_{Dep} = 650 \degree C$

### External Quantum Efficiency

- **GaInP Cell**:
  - External Quantum Efficiency: 11.1 mA/cm$^2$
- **GaAs Cell**:
  - External Quantum Efficiency: 13.8 mA/cm$^2$

### Current Density vs. Voltage

- **AM1.5G**:
  - $J_{SC} = 11.16 \pm 0.15$ mA/cm$^2$
  - $V_{OC} = 2.40 \pm 0.02$ V
  - $FF = 88.4\% \pm 1.2\%$
  - $\eta = 23.7\% \pm 0.3\%$

- **HC122W**:
  - NREL certified
Electroluminescence of the tandem device reveals subcell $V_{OC}$’s of 1.40 and 1.00 V for GaInP and GaAs, respectively.

- $n \approx 1$ diode ideality at $J_{SC}$ for both cells, implying good material quality.
Boosting Top Cell Current

Growth Direction

- p⁺-GaInP:Zn BSF
- n-GaAs:Se base
- n⁺-GaInP:Se window
- n⁺⁺-GaAs:Se TJ layer
- p⁺-GaInP:Zn BSF
- p-GaInP:Zn base
- Se Diffusion
- n-GaInP:Se emitter
- n⁺-GaAs:Se Contact
- n-GaInP:Se etch stop
- n-GaInP:Se buffer
- n-GaAs:Se Substrate

SIMS Data

Se Diffusing into GaInP Base

Growth Direction

HB725 Se = 15 sccm

[Se] P Signal

Se Concentration (cm⁻³)

Depth (µm)
Boosting Top Cell Current

- n-GaAs:Se base
- n⁺-GaInP:Se window
- n⁺⁺-GaAs:Se TJ layer
- p⁺-GaInP:Zn BSF
- p-GaInP:Zn base
- n-GaInP:Se emitter
- n⁺-GaAs:Se Contact
- n-GaInP:Se etch stop
- n-GaInP:Se contact
- n-GaAs:Se Buffer
- n-GaAs Substrate

Se Diffusion

SIMS Data

- GaAs Contact
- GaInP

Se Concentration (cm⁻³)

0.0 0.1 0.2 0.3
Depth (µm)

Se Diffusing into GaInP Base

HB725 Se = 15 sccm
HC063 Se = 3 sccm

P Signal

0 20 40 60 80 x10⁶
GaInP
Increasing Top Cell Current

IQE as a function of Se Flow ($Q_{\text{Se}}$) during contact growth

<table>
<thead>
<tr>
<th>$Q_{\text{Se}}$ (sccm)</th>
<th>$J_{\text{SC}}$ (mA/cm$^2$)</th>
<th>$t_{\text{emitter}}$ (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>exp model</td>
<td></td>
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<tr>
<td>△</td>
<td>15</td>
<td>10.7</td>
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<tr>
<td>△</td>
<td>9</td>
<td>11.2</td>
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<tr>
<td>△</td>
<td>6</td>
<td>12.2</td>
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Simply reducing GaAs contact doping boosts GaInP IQE -> limit is structure rather than material quality.
Increasing Top Cell Current

IQE as a function of Se Flow ($Q_{Se}$) during contact growth

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<td>△</td>
<td>30 nm emitter</td>
<td>14.4</td>
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30 nm emitter would yield 14.4 mA/cm$^2$ of current (before reflection losses)

$$\eta = 23.7\% \times \frac{14.10 \text{ mA}}{11.16 \text{ mA/cm}^2} \times \frac{2.43 \text{ V}}{2.40 \text{ V}} = 30.3\%$$

Possible with current material quality!
Conclusions

• III-V Tandem Devices with significantly reduced deposition cost are possible via D-HVPE
• Bulk material quality is not limiting device performance
• >30% efficiency possible with current material quality and only structural improvements to device
Thank You

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