Progress in High-Efficiency III-V Multijunction Concentrator Solar Cells


Spectrolab, Inc., Sylmar, CA

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• Solar spectrum and theoretical efficiency
• **Multijunction** cell architectures capable of >50%
• Metamorphic (MM) semiconductor materials  
  ⇒ flexibility in bandgap for multijunction cells
• Experimental results on **metamorphic** (MM) and **lattice-matched** (LM) 3-junction cells over 40% efficiency
• Dislocations and recombination in MM materials
• Bandgap - $V_{oc}$ offset and diode ideality factor for LM and MM
• Highly lattice-mismatched ~1-eV MM GaInAs subcells
• **4-junction** terrestrial concentrator cells with reduced series resistance power losses
Wide-bandgap tunnel junction

Ga(In)As middle cell

Tunnel junction

Buffer region

Ge bottom cell

Lattice-Matched (LM)

Lattice-Mismatched or Metamorphic (MM)
Solar Spectrum Partition for 3-Junction Cell

Current Density per Unit Wavelength (mA/(cm²·μm))

Wavelength (nm)

External Quantum Efficiency (%)

AM1.5D, low-AOD
AM1.5G, ASTM G173-03
AM0, ASTM E490-00a

1.79 eV
1.31 eV
0.67 eV
External QE of LM and MM 3-Junction Cells

- AM1.5D, low-AOD
- AM1.5G, ASTM G173-03
- AM0, ASTM E490-00a
- EQE, lattice-matched
- EQE, metamorphic
3-junction $E_{g1}/E_{g2}/0.67$ eV cell efficiency

- 240 suns (24.0 W/cm²), AM1.5D (ASTM G173-03), 25°C
- Ideal efficiency -- radiative recombination limit

$E_{g1} = \text{Subcell 1 (Top) Bandgap (eV)}$

$E_{g2} = \text{Subcell 2 Bandgap (eV)}$

Disordered GaInP top subcell

Ordered GaInP top subcell

- MM
- LM
- 40.7%
- 40.1%
- 54%
- 52%
- 50%
- 48%
- 46%
- 44%
- 42%
- 40%
- 38%
Record 40.7%-Efficient Concentrator Solar Cell

- Highest solar conversion efficiency for any type of photovoltaic device demonstrated to date
- First solar cell of any kind to reach over 40% efficiency

Concentrator cell light I-V independently verified by J. Kiehl, T. Moriarty, K. Emery – NREL
Lattice-Matched and Metamorphic Cells Over 40%

<table>
<thead>
<tr>
<th></th>
<th>Concentrator Cells</th>
<th>1-sun Cells</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Latt.-matched</td>
<td>Metamorphic</td>
</tr>
<tr>
<td>$V_{oc}$</td>
<td>3.054 V</td>
<td>2.911 V</td>
</tr>
<tr>
<td>$J_{sc/inten.}$</td>
<td>0.1492 A/W</td>
<td>0.1596 A/W</td>
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<tr>
<td>$V_{mp}$</td>
<td>2.755 V</td>
<td>2.589 V</td>
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<tr>
<td>FF</td>
<td>0.881</td>
<td>0.875</td>
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<tr>
<td>conc.</td>
<td>135 suns</td>
<td>240 suns</td>
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<tr>
<td>area</td>
<td>0.2547 cm²</td>
<td>0.267 cm²</td>
</tr>
<tr>
<td>Eff.</td>
<td>40.1%</td>
<td>40.7%</td>
</tr>
</tbody>
</table>

Designated-area efficiency at 25C

Total-area efficiency at 25C

AM1.5D, low-AOD spectrum

AM1.5G 1 sun = 0.100 W/cm²
Record Cell Efficiencies for a Variety of PV Technologies

Chart courtesy of Bob McConnell, NREL
3-Junction Theoretical Eff. — Vary \(E_{g1}\) and \(E_{g2}\)

3-junction \(E_{g1}/E_{g2}/0.67\) eV cell efficiency

240 suns (24.0 W/cm\(^2\)), AM1.5D (ASTM G173-03), 25°C

Ideal efficiency -- radiative recombination limit

\(E_{g1} = \) Subcell 1 (Top) Bandgap (eV)

\(E_{g2} = \) Subcell 2 Bandgap (eV)

- **Disordered GaInP top subcell**
- **Ordered GaInP top subcell**

- MM
- LM

Ideal efficiency

38%
42%
44%
46%
50%
52%
54%
40.7%
40.1%
48%
3-junction $E_{g1}/E_{g2}/0.67$ eV cell efficiency

- 240 suns (24.0 W/cm²), AM1.5D (ASTM G173-03), 25°C
- Series resistance and grid shadowing included

$E_{g1}$ = Subcell 1 (Top) Bandgap (eV)
$E_{g2}$ = Subcell 2 Bandgap (eV)

Disordered GaInP top subcell
Ordered GaInP top subcell
**3-Junction Efficiency – Based on Expt. Values**

**3-junction $E_{g1}/E_{g2}/0.67$ eV cell efficiency**

240 suns (24.0 W/cm$^2$), AM1.5D (ASTM G173-03), 25°C

Normalized to experimental 3J cell Voc and Jsc

- Disordered GaInP top subcell
- Ordered GaInP top subcell

$E_{g1} =$ Subcell 1 (Top) Bandgap (eV)

$E_{g2} =$ Subcell 2 Bandgap (eV)
Record Cell Performance vs. Concentration

Efficiency (%) and $V_{oc} \times 10$ (V)

Fill Factor (%)

**Eff.**
- 40.1% LM
- 40.7% MM

**$V_{oc} \times 10$**
- 38.5%

at 630 suns

**FF**
- 40.7% MM
- 40.1% LM
- 38.5%

at 630 suns

(1 sun = 0.100 W/cm²)
Jsc vs. Voc Measurements for MM and LM GaInAs and GaInP

- MM GaInAs
- MM GaInP
- MM 3J cell data
- LM GaInAs
- LM GaInP
- LM 3J cell data

- Jo1, Jo2 fit
- sum of Voc, MM 3J subcells
- sum of Voc, LM 3J subcells
Diode Ideality vs. Voltage for MM and LM GaInAs & GaInP

- MM, 8%-In GaInAs
- LM, 1%-In GaInAs
- MM, 56%-In GaInP
- LM, 49.5%-In GaInP
Visualizing Dislocations in III-V Materials
• Low dislocation density in active cell layers in top portion of epilayer stack:
  \[ \sim 2 \times 10^5 \text{ cm}^{-2} \] from EBIC and CL meas.

• Dislocations confined to graded buffer layers in bottom portion of epilayer stack
High-Resolution XRD Reciprocal Space Map (RSM)

- GaInP/ 8%-In GaInAs/ Ge metamorphic (MM) cell structure
- Nearly 100% relaxed step-graded buffer → removes driving force for dislocations to propagate into active cell layers
- 56%-In GaInP top cell pseudomorphic with respect to GaInAs middle cell
Dislocation Imaging in 23%-In GaInAs

23%-In GaInAs double heterostructure on Ge

Cathodoluminescence (CL)

\[ \text{disloc. density} = 4.4 \times 10^6 \text{ cm}^{-2} \]

Plan-View Transmission Electron Microscopy (TEM)

\[ \text{disloc. density} = 3.1 \times 10^6 \text{ cm}^{-2} \]
Time-Resolved PL of LM & MM Double Heterostructures

Indium Mole Fraction of GaInAs Lattice-Matched to Base (%)

\[ \tau_{\text{eff}} \text{ Measured by TRPL (ns)} \]

**Base Material**

Recent data
- nid-GaInAs, recent data
- p-GaInP (disordered)

Previous data
- nid-GaInAs
- nid-GaInP (ordered)
- nid-GaInP (disordered)

\[ E_g = 1.407 \text{ eV} \]

\[ 1.813 \text{ eV} \]

\[ 1.887 \text{ eV} \]

\[ 1.311 \text{ eV} \]

\[ 1.114 \text{ eV} \]

\[ 0.994 \text{ eV} \]

\[ 1.736 \text{ eV} \]

\[ 1.807 \text{ eV} \]

\[ 1.529 \text{ eV} \]

\[ 1.619 \text{ eV} \]

*Time-resolved PL meas. courtesy of W. Metzger, B. Keyes, and R. Ahrenkiel – NREL*
Quantum Eff. of Metamorphic GaInAs and GaInP Cells on Ge

- GaInAs, 1.6% mismatch (no AR, normalized)
- GaInAs, 0.5% mismatch
- GaInAs, 0% mismatch
- GaInP, 0.5% mismatch, disordered
- GaInP, 0% mismatch, disordered

Photon Energy (eV)

Quantum Efficiency (%)
Bandgap - Voltage Offset \((E_g/q) - V_{oc}\) for Single-Junction Solar Cells

\(V_{oc}\) of solar cells with wide range of bandgaps and comparison to radiative limit

- \(V_{oc}\) (V)
- \(E_g/q\) (V)
- \((E_g/q) - V_{oc}\) (V)
- radiative limit

- d-AlGaInP
- 0.97-eV GaInAs
- GaInNAs
- 1.10-eV GaInAs
- 1.24-eV GaInAs
- 1.30-eV GaInAs
- A\text{GaInAs}
- AGaInAs
- d-GaInP
- d-A\text{GaInP}
- d-A\text{GaInP}
- d-A\text{GaInP}
Voc of solar cells with wide range of bandgaps and comparison to radiative limit
Metamorphic (MM) 3-Junction Cells — Inverted 1.0-eV GaInAs Subcell

Growth on both sides of GaAs substrate

Growth on one side of GaAs or Ge substrate, followed by substrate removal
Solar Spectrum Partition for 3-Junction Cell

![Graph showing current density per unit wavelength and external quantum efficiency for different solar spectrum conditions: AM1.5D, low-AOD, AM1.5G, ASTM G173-03, AM0, ASTM E490-00a.](image)
3-Junction Theoretical Eff. — Vary $E_{g2}$ and $E_{g3}$

3-junction 1.9 eV/ $E_{g2}$/ $E_{g3}$ cell efficiency
500 suns (50 W/cm$^2$), AM1.5D (ASTM G173-03), 25°C
Ideal efficiency -- radiative recombination limit

$E_{g2}$ = Subcell 2 Bandgap (eV)
$E_{g3}$ = Subcell 3 Bandgap (eV)
4-Junction Terrestrial Concentrator Cell

- Divides available current density above GaAs $E_g$ among 3 subcells instead of 2
- High-voltage, low-current design
- Approx. $2/3$ current density of 3-junction cell
- $(2/3)^2$ or less than half of series resistance loss
  $\rightarrow$ Crucial for concentrators
4-Junction Theoretical Efficiency

4-junction 1.9 eV / $E_{g2}$ / $E_{g3}$ / 0.67 eV cell efficiency

500 suns (50 W/cm²), AM1.5D (ASTM G173-03), 25°C

Ideal efficiency -- radiative recombination limit

$E_{g3}$ = Subcell 3 Bandgap (eV)

$E_{g2}$ = Subcell 2 Bandgap (eV)
External QE – 4-Junction Concentrator Cell

- GaInP subcell 1 (top cell): 1.86 eV
- AlGaInAs subcell 2: 1.62 eV
- GaInAs subcell 3: 1.38 eV
- Ge subcell 4: 0.70 eV
4-Junction Light I-V at 250 Suns – Active and Inactive Ge

<table>
<thead>
<tr>
<th></th>
<th>3J Concentrator Cells</th>
<th>4J Concentrator Cells</th>
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<tbody>
<tr>
<td></td>
<td>Latt.-matched</td>
<td>Metamorphic</td>
</tr>
<tr>
<td></td>
<td>4J Cell</td>
<td>Inactive Ge (3J)</td>
</tr>
<tr>
<td>$V_{oc}$</td>
<td>3.089</td>
<td>2.922</td>
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<tr>
<td>$J_{sc}$/inten.</td>
<td>0.1431</td>
<td>0.1575 A/W</td>
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<tr>
<td>$V_{mp}$</td>
<td>2.749</td>
<td>2.565</td>
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<tr>
<td>FF</td>
<td>0.882</td>
<td>0.855</td>
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<td>conc.</td>
<td>236</td>
<td>179</td>
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<td>area</td>
<td>0.269</td>
<td>0.378 cm$^2$</td>
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<tr>
<td>Eff.</td>
<td>39.0%</td>
<td>39.3%</td>
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</table>

Aperture-area efficiency, 25C
AM1.5D, low-AOD spectrum
Independently confirmed meas.

Aperture-area efficiency, 25C
AM1.5D ASTM G173-03
Preliminary measurement
5- and 6-Junction Cells

- Divides available current density above GaAs $E_g$ among 3-4 subcells
- Allows low-current GaInNAs cell to be matched to other subcells
- Lower series resistance

Ref.: U.S. Pat. No. 6,316,715, Spectrolab, Inc., filed 3/15/00, issued 11/13/01.
• Energy generation increases from 3J → 4J → 5J → 6J, due to series res., better use of spectrum
• Large difference between 5J and 6J due to inclusion of ~1-eV subcell
• $\eta > 50\%$ achievable by solar spectrum division in MJ cells with the right subcell bandgaps

• **4-6 junction** terrestrial cells $\rightarrow$ strong advantage at high concentrations from lower series resistance losses $\rightarrow$ **35.7%** 4J conc. cell measured

• **Metamorphic materials give new opportunity for bandgap engineering**
  ✓ High $V_{oc}$ and $\tau$ demonstrated on **1.1-eV** and **1.3-eV** MM GaInAs subcells

• Faster voltage increase with ↑ incident intensity meas. for MM cells

• New heights in terrestrial concentrator cells reported here:
  • **40.7%** metamorphic (MM) 3J cell
  • **40.1%** lattice-matched (LM) 3J cell

$\rightarrow$ **First solar cells to reach over 40%**

$\rightarrow$ Highest solar conversion efficiency for PV device of any kind to date

$\rightarrow$ **Metamorphic cells now exceed best lattice-matched designs**