Advances in Epitaxial GaInP/GaAs/Si Triple Junction Solar Cells

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III-V on Si

Motivation

- Silicon solar cells
  - Limited to 29.4 % efficiency\(^1\)
  - Low cost of manufacturing

- III-V multi-junction solar cells
  - Highest efficiencies (38.8 %)\(^2\)
  - Proven stability (space)
  - Substrates costly

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### Theoretical limit: \( \eta = 43 \% \)

III-V on Si

Challenges

- III-V on Si
  - Polar (III-V) on non-polar (Si) crystals
  - Lattice mismatch of ~4%

→ III-V epitaxy on Si not trivial
Ill-V on Si
MOVPE Approach

Ternary Semiconductors
- direct
- indirect

Band gap [eV]

Lattice constant [Å]

GaP
Si
GaAs
InGaAs
GaInP
InP
InAs
Ge
Si
GaP
GaAs
InGaAs
GaInP
InP
InAs
Ge
Si
GaP
GaAs
InGaAs
GaInP
InP
InAs
Ge
Si
GaP
GaAs
InGaAs
GaInP
InP
InAs
Ge
Silicon bottom cell
Ill-V on Si
MOVPE Approach
### III-V on Si

#### MOVPE Approach

<table>
<thead>
<tr>
<th>Ternary Semiconductors</th>
<th>Band gap [eV]</th>
<th>Lattice constant [Å]</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaP</td>
<td>2.3</td>
<td>5.4</td>
</tr>
<tr>
<td>AlP</td>
<td>2.3</td>
<td>5.4</td>
</tr>
<tr>
<td>AlAs</td>
<td>2.3</td>
<td>5.4</td>
</tr>
<tr>
<td>GaInP</td>
<td>2.3</td>
<td>5.4</td>
</tr>
<tr>
<td>InGaAs</td>
<td>2.3</td>
<td>5.4</td>
</tr>
<tr>
<td>InP</td>
<td>2.3</td>
<td>5.4</td>
</tr>
<tr>
<td>Si</td>
<td>1.1</td>
<td>5.4</td>
</tr>
<tr>
<td>Ge</td>
<td>0.7</td>
<td>5.4</td>
</tr>
</tbody>
</table>

**MOVPE Approach**

- **GaInP top cell**
- **GaAs middle cell**
- **GaAs$_y$P$_{1-y}$**
- **GaP**
- **Si bottom cell**

**Diagram**: Ternary Semiconductors with band gap and lattice constant values.
1st Gen III-V on Si Solar Cell (2017)

Characterisation

- Crystal defects limit voltage and quantum efficiency (TDD : 1.4×10^8 cm⁻²)
1st Gen III-V on Si Solar Cell
Defect Characterisation

- Crystal defects limit voltage and quantum efficiency (TDD : 1.4×10^8 cm^-2)
- GaP nucleation on Si
  - Stacking fault pyramids 6×10^7 cm^-2
1st Gen III-V on Si Solar Cell

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Feifel et al. *Journal of Crystal Growth*, vol. 532, p. 125422, 2020
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[Diagram of solar cell structure]

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Electron Channeling Contrast Imaging

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Reduction of Defect Density

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Optimization of GaP nucleation

Feifel et al. *Journal of Crystal Growth*, vol. 532, p. 125422, 2020
2nd Gen III-V on Si Solar Cell (2019)

IV-Characteristics

- IV:
  - Increase in $V_{OC}$ by +296 mV
  - No change in $J_{SC}$
2\textsuperscript{nd} Gen III-V on Si Solar Cell

**EQE**

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- **EQE:**
  - GaInP bandgap adjusted
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Feifel et al. *Solar RRL*, vol. 3, p. 1900313, 2019
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  - Poor light trapping in Si bottom cell
  - Strong parasitic absorption in GaAsP buffer for 700nm < $\lambda$ < 900 nm
2nd Gen III-V on Si Solar Cell
Parasitic Absorption

- Increase bandgap of buffer layers to \( E_g \geq 1.8 \text{ eV} \equiv 690 \text{ nm} \)
- \( \text{Al}_{0.29}\text{Ga}_{0.71}\text{As} \) as last buffer layer

![Diagram showing bandgap and x [\( \mu \text{m} \)] for GaAs\(_y\)P\(_{1-y}\) and Al\(_x\)Ga\(_{1-x}\)As\(_y\)P\(_{1-y}\) layers with thicknesses and compositions as text.]
2\textsuperscript{nd} Gen III-V on Si Solar Cell
Parasitic Absorption

- Increase bandgap of buffer layers to $E_g \geq 1.8$ eV $\equiv 690$ nm
- $\text{Al}_{0.29}\text{Ga}_{0.71}\text{As}$ as last buffer layer
- Decreased threading dislocation density

![Graph showing threading dislocation density for GaAsyP1-y and AlxGa1-xAsyP1-y layers](image)

<table>
<thead>
<tr>
<th>GaAsyP1-y $(E_g \geq 1.4$ eV)</th>
<th>$10^7$</th>
<th>$10^8$</th>
</tr>
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<tbody>
<tr>
<td>GaP/Si substrate</td>
<td></td>
<td></td>
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<tr>
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</tr>
<tr>
<td>GaAs$<em>{0.93}$P$</em>{0.07}$</td>
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- GaP
- $\text{Si}$
- $\text{GaP}$
3rd Gen III-V on Si Solar Cell (2019)

EQE:

- No significant change for GaInP and GaAs subcells
3rd Gen III-V on Si Solar Cell

EQE:

- No significant change for GaInP and GaAs subcells
- Improved/recovered light trapping
- No significant parasitic absorption
- +2.3 mA/cm² increase for Si subcell
3rd Gen III-V on Si Solar Cell
IV-Characteristics

- **EQE:**
  - No significant change for GaInP and GaAs subcells
  - Improved/recovered light trapping
  - No significant parasitic absorption
  - +2.3 mA/cm² increase for Si subcell

- **IV:**
  - Lower TDD leads to increased $V_{OC}$
  - +2.2 mA/cm² gain in current
  - 24.3 % efficiency under AM1.5g (4 cm²)
  - Close to $V_{OC}$ carrier transport issue occurs

### IV Characteristics

- **AM1.5g**
  - **$V_{OC}$ [V]**: 2.323, 2.619, 2.661
  - **$J_{SC}$ [mA/cm²]**: 10.0, 10.0, 12.2
  - **FF [%]**: 84.3, 85.0, 74.5
  - **η [%]**: 19.7, 22.3, 24.3
3rd Gen III-V on Si Solar Cell

Temperature dependent IV

- S-shape in IV-characteristics
- Strong dependence on cell temperature → Majority barrier
- Barrier height\(^1\) 280 meV

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- 2-step MOVPE process
  - Oxidation of Al\(_{0.3}\)Ga\(_{0.7}\)As layer during transfer causes barrier

-reactor 1 (CRIUS CCS)
-reactor 2 (AIX2800G4)
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  - Oxidation of Al\(_{0.3}\)Ga\(_{0.7}\)As layer during transfer causes barrier
  - 5 nm GaAs cap to suppress oxidation

\[
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Reactor 1 (CRIUS CCS)
Reactor 2 (AIX2800G4)
4th Gen III-V on Si Solar Cell (2020)

IV-Characteristics

- IV:
  - No sign of majority barrier
  - Fill factor increased to 80.2 %
  - Record efficiency: 25.9 % @ AM1.5g

1) Verified by Fraunhofer ISE CalLab
4th Gen III-V on Si Solar Cell

EQE

- **IV:**
  - No sign of majority barrier
  - Fill factor increased to 80.2 %
  - **Record efficiency: 25.9 % @ AM1.5g**

- **EQE:**
  - Increased EQE for GaAs and GaInP cell (structural changes in cell structure)
  - Current matching to be adjusted in future device

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1) Verified by Fraunhofer ISE CalLab
2) Details in upcoming publication
Summary

- MOVPE-growth of GaInP/GaAs/Si triple junction solar cells
- **Certified 25.9 % conversion efficiency** @ AM1.5g for 4 cm² cell

- Rapid efficiency improvement from 19.7 % (2017) to 25.9 % (2020)
  - Stacking fault (pyramid) density in GaP on Si nucleation layer reduced from $6 \times 10^7$ cm$^{-2}$ to $<10^5$ cm$^{-2}$
  - Parasitic absorption in GaAs$_y$P$_{1-y}$ buffer structure suppressed by using Al$_x$Ga$_{1-x}$As$_y$P$_{1-y}$
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- **Outlook:**
  - Record cell is grown on low-cost Si surface finish (no CMP)
Thank you for listening!

Fraunhofer Institute for Solar Energy Systems ISE

Markus Feifel

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