Developing Next-Gen Si Solar Cells to Enable Higher-Efficiency Modules at Today’s Cost

**Foundational Knowledge**

Developed passivated tunnel contacts for advanced cell architecture

Developed Tabula Rasa wafer treatment to prevent O-precipitation

**Innovation to Application**

High efficiency >23%, low cost industrial-size cell on n-Cz wafer by 2018; currently 21.5%

Exploring novel transparent and conductive micro composites

**Integration to Impact**

Impact entire c-Si PV market

NREL as US-based, internationally recognized Si PV research hub

Creates Si industry workforce

**Systems Engineering & Integration**

**Decision Science & Analysis**

**Power Systems & Electrical Engineering**

**Applied Materials Science & Engineering**

**Chemical Engineering**

**Advanced Computer Science, Visualization & Data**

**MIT**

**GIT**

**ASU**

**CSM**

**NIST**

**FhISE**

**UNSW**
Goal: Next generation Si solar cells enable >22% modules at costs of present 17% mainstream Si PV modules. This leads to grid parity.

Diffused junctions are replaced by deposited “passivated contact” junctions, with very thin dielectric passivating tunneling layer combined with “workfunction-setting” layer to induce junction in an underlying wafer.

NREL developed:
- tunneling passivated contacts (Poly-Si/SiO₂/n-Cz) oxygen precipitate suppression treatments for bulk n-Cz → high performance B emitter
- Front grid cells in 2013 – 2015 (20% n-PERT and 21.5% B-front, n+-poly back)
- Record 29.8% Si/III-V stacked tandem

Presently, we are developing advanced, industrially robust Si cells with passivated contact pads on the back (IBC cells). This involves bulk, contact, interface, and device science with MIT, GIT, ASU, CSM.

Nemeth et al., IEEE PVSC 2014; D. Young et al., IEEE JPV 2015.
From baseline n-Cz PERT (FY13) to high performance pasivated contact cell (FY14-15)

**PERT cell:** diffused phosphorus back electrode with patterned metal contact (complicated), 20% efficient, could reach ~ 22%.

**Full area passivated back contact cell:** Simpler process, high industry potential, best at 21.5% (on FZ Si), potential for >23%.
Challenge I: O-precipitates in n-Cz wafers

TEM of O-precipitate with dislocation loops

n—CZ wafer “as received”

n—CZ wafer with TR

B diffusion (850/950C) and deep drive-in/oxidation (980C)
Oxide-passivated + Forming Gas Anneal

Result: deep B drive-in “develops” precipitate rings from nuclea
TR can improve wafer quality and uniformity in B-diffused cells

LaSalvia & Nemeth, et al., IEEE PVSC 2015
Challenge 2: Passivated full-area contacts with induced junctions to Si

1. Direct metal contact to Si = strong recombination due to interface DOS within Si gap. Passivated contact separates metal from Si.
2. Passivated contacts don’t require dopant diffusions and thus minimize surface and Auger recombination.
3. No complicated contact patterning. Metal contacts highly doped, defective transport layer, separated from wafer by buffer (tunneling) layer.

Passivated contacts with no states in Si gap for ultrahigh efficiency

- Dielectric buffer layer (SiO₂, Al₂O₃) with tunneling states, +doped poly-Si transport layer
- a-Si:H passivated full area contact HJ cell
- Bandgap-offset tuned, buffered heterojunction for selective carrier transport
Materials Choices for Passivated Contacts

1. Transport layer workfunction determines the type of induced junction to Si wafer.
2. Transport layer band offsets tune the carrier selectivity in addition to junction field.
3. Buffer/tunneling layer in between transport layer and Si wafer ensures good chemical passivation of the wafer. Doped poly-Si/tunnel SiO₂ = good performance, high T

Compiled from various sources and DFT-simulated by Y. Liu and J.W Luo, NREL

C. Battaglia et al., IEEE PVSC 2014
R. Peibst et al., IEEE PVSC 2014
W. Nemeth et al., IEEE PVSC 2014
E. Yablonovitch et al., APL 1985
F. Feldmann et al., APL 2014
N-Cz: Passivated B-emitter, passivated n-poly contact, non-metallized device structure: all enabling 23% devices before metallization

<table>
<thead>
<tr>
<th>Structure</th>
<th>$i_{Voc}$ (mV)</th>
<th>$J_0$ (fA/cm²)</th>
<th>$T_{bulk}$ ($\mu$s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passivated B emitter on textured n-Cz, 130 $\Omega$/sq, Al₂O₃/SiNₓ - symmetric</td>
<td>717</td>
<td>17.1 (each side)</td>
<td>3732</td>
</tr>
<tr>
<td>n+ poly Si/SiO₂ on KOH-planarized, initially textured n-Cz Si - symmetric</td>
<td>735</td>
<td>2.1 (each side)</td>
<td>7562</td>
</tr>
<tr>
<td>p+ poly Si/SiO₂ contact to saw-damage removed n-Cz Si - symmetric</td>
<td>709</td>
<td>11 (each side)</td>
<td></td>
</tr>
<tr>
<td><strong>Solar cell: B-emitter, n+ poly-Si/SiO₂ BSF, n-Cz, before metallization.</strong></td>
<td><strong>724</strong></td>
<td><strong>11.6 (total)</strong></td>
<td><strong>4156</strong></td>
</tr>
</tbody>
</table>

*LaSalvia & Nemeth, et al., IEEE PVSC 2015*
Full-area passivated tunneling BSF contact cell
(NREL, FPACE-II work synergistic to core agreement)

Acknowledgement for n-FZ diffused emitter:
Stefan Glunz, Jan Benick, Martin Hermle
(Fraunhofer ISE)

Poly-Si passivated contact:
B. Nemeth et al., 40th IEEE PVSC, 2014

<table>
<thead>
<tr>
<th>Sinton PCD-lifetime</th>
<th>Cell</th>
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<tbody>
<tr>
<td>ImV_{oc} (mV) 698</td>
<td>V_{oc} (mV) 693</td>
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<tr>
<td>\tau_{hil} (us) --</td>
<td>J_{sc} (mA/cm^2) 39.55</td>
</tr>
<tr>
<td>J_{o,tot} (fA/cm^2) 55</td>
<td>FF (%) 78.37</td>
</tr>
<tr>
<td></td>
<td>Eff. (%) 21.48</td>
</tr>
</tbody>
</table>

H.C. Yuan et al., Si PV Workshop 2014; B. Lee, EuPVSEC 2014
Development of World Record GaInP/Si Dual-Junction, One-Sun Solar Cell

The device structure integrates a 1.8-eV GaInP top junction with a silicon bottom junction, with a four-terminal interconnection. The resulting device is pictured at right.

- Cost-effective solar cells with efficiency greater than possible with conventional silicon could enable a very large market for low-concentration photovoltaics.
- A two-junction structure with a silicon bottom junction is an attractive path to this goal.
- NREL developed a new device structure combining a III-V GaInP top junction and a silicon bottom junction, and demonstrated a record 29.8% efficiency – significantly exceeding the best conventional silicon efficiency of 25.6%.
- The four-terminal structure allows ease of construction, and optimal energy production under real-world operating conditions.
- We are presently developing an improved, manufacturable bonding technique to enable transfer of this structure to industry.

Science to advance Si PV (single J and tandems)

- Passivated contact requires much deeper understanding to become relevant:
  - Conduction mechanisms and engineered tunneling in the dielectric layer
  - Engineering of the interfaces, and new materials for the “workfunction-setting” layer for higher carrier selectivity
  - Understanding and overcoming the difficulty of p-type passivated contacts performance
  - Understanding and overcoming the strong sensitivity to metal deposition.

- Device – level science and engineering:
  - Light management – novel and efficient structures both on front and the back, enabling blue, visible, and near-gap light to be fully utilized (plus low cost).
  - Light management in the device context – compatibility (esp. with back contacts)
  - Novel metallization and contacting techniques, esp. for the IBC cells.

- Tandems require new, advanced approaches:
  - Integrating Si and III-V optically and electrically
  - Low cost