Highest Efficiency Cell Technologies

Stanford – 25% rear contact

UNSW – 25% PERC

Passivated Contacts 25-26.3%

School of Photovoltaic and Renewable Energy Engineering
Hydrogen very important for p-type wafers

- **p-type Si**: $\text{H}^+$
- **Dangling bond**: $\text{D}^+$
- **Fe$_i$**$^+$, **Cr$_i$**$^+$, **BO**$^+$

**High mobility/reactivity**

- **n-type Si**: $\text{H}^-$

**H-BO formation unfavorable in p-type silicon**

**Must consider the charge state of hydrogen and defects**
Use carrier injection and cell design to manipulate hydrogen

- Now many newer and better techniques for controlling the H charge state
Application to p-type Cz wafers

- Main issue – solving LID (B-O defects)
- Accelerated defect formation
- UNSW Advanced Hydrogenation of B-O defects
- LID in p-type Cz PERC cell – Solved!!

Sequential Photoluminescence Images
• Provide control of the hydrogen charge state
• New tools implementing UNSW hydrogenation
  o Asia Neo Tech (Taiwan – LED based tool)
  o Ke Long Wei (China – Broad spectrum tool)
  o Schmid (Germany)
  o Dr Laser (China – Laser-based tool)
  o Meyer Berger (Switzerland)
• New generation of tools in 2017 with solution for multi LID
Evaluation of commercial prototypes

Cz PERC hydrogenation tools evaluation

Normalized Voc vs Light soaking time (hrs)
## Advanced Hydrogenation of P-type Cz PERC

### Table:

<table>
<thead>
<tr>
<th>PERC cell producers</th>
<th>Hydrogenation Efficiency Increases (% absolute)</th>
<th>48 h light soak stable?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturer A</td>
<td>+0.8%</td>
<td>Yes</td>
</tr>
<tr>
<td>Manufacturer B</td>
<td>+1.0%</td>
<td>Yes</td>
</tr>
<tr>
<td>Manufacturer C</td>
<td>+0.7%</td>
<td>Yes</td>
</tr>
<tr>
<td>Manufacturer D</td>
<td>+0.9%</td>
<td>Yes</td>
</tr>
<tr>
<td>Manufacturer E</td>
<td>+1.5%</td>
<td>Yes</td>
</tr>
<tr>
<td>Manufacturer F</td>
<td>+0.8%</td>
<td>Yes</td>
</tr>
<tr>
<td>Manufacturer G</td>
<td>+1.8%</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Average Increase</strong></td>
<td><strong>+1.1% absolute</strong></td>
<td><strong>Yes</strong></td>
</tr>
</tbody>
</table>

### Graph:

- **Efficiency**
  - Hydrogenated group
  - Non-hydrogenated group

- **Efficiency (%):**
  - Before hydrogenation
  - After hydrogenation
  - 48hr light soak

- **Arrow Indications:**
  - 8 seconds process
  - Final efficiency higher
  - Final efficiency stable
  - PERC cells need this
H can passivate much more than B-O defects

Localised Control of the H Charge State

- Innovative hydrogen charge state control has large impact on both diffusivity & reactivity of hydrogen atoms in silicon
- Transformation of low quality silicon into high quality silicon (where PL count saturates)
- Simple 8 second process
- US Patent awarded Nov 2015 without modification

PL Images before & after localised hydrogenation. Wafer T = 250 degC
Advanced Hydrogenation also works well on n-type!
# Cell Technology Trends – Bloomberg New Energy

<table>
<thead>
<tr>
<th>Efficiency</th>
<th>2015</th>
<th>2018</th>
<th>2025</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>P-type multi Al-BSF</td>
<td>79%</td>
<td>65%</td>
</tr>
<tr>
<td></td>
<td>P-type multi PERC</td>
<td>3%</td>
<td>10%</td>
</tr>
<tr>
<td></td>
<td>P-type mono Al-BSF</td>
<td>10%</td>
<td>4%</td>
</tr>
<tr>
<td></td>
<td>P-type mono PERC/L</td>
<td>3%</td>
<td>10%</td>
</tr>
<tr>
<td></td>
<td>N-type mono PERT</td>
<td>1%</td>
<td>3%</td>
</tr>
<tr>
<td></td>
<td>N-type mono HIT</td>
<td>2%</td>
<td>4%</td>
</tr>
<tr>
<td></td>
<td>N-type mono IBC</td>
<td>3%</td>
<td>4%</td>
</tr>
<tr>
<td>High</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Stanford** – 25% rear contact
- **UNSW** – 25% PERC
- **Passivated Contacts** 25-26.3%

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**Textured front surface**

- N-type monocrystalline silicon wafer

**Passivated Contacts**

- a-Si:H
  - p+ silicon
  - p-silicon
  - oxide
  - p+ silicon
  - a-Si:H (textured)
  - rear contact
  - TCO
  - Electrode
  - ~10nm
  - ~250µm
  - ~20nm

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**Diagram**

- Finger
- "Inverted" pyramids
- n-type c-Si
- a-Si:H
- p+ silicon
- p-silicon
- oxide
- p+ silicon
- a-Si:H (textured)
- rear contact
- TCO
- Electrode
LID in multi-PERC is a serious problem

PL response as function of light-soaking time
Defect causing LID in mc-Si PERC also occurs in mono-Si
Comparison of Type 1 & 2 Defects
Identification of same defect in FZ wafers

- **FZ defect type 1**
- **FZ defect type 2**

**Graph:**
- **Y-axis:** Normalised PL count
- **X-axis:** Time (hours)
- The graph shows the decrease in normalised PL count over time for both FZ defect types.
SiNx coated p-type FZ wafers from Sperber et al. from Konstanz at 250°C.
Elimination of LID in mc-Si PERC cells

- Identification of the defect in mc-Si
- Multiple energy levels in band-gap
- H accelerates evolution of defect
- H ultimately passivates defect
- Need >1,000 hours of light-soaking
- Common in n-type material
- Can occur in any wafers including mono wafers

UNSW laser hydrogenation

Top: Relative change in $V_{oc}$ of a mc-Si PERC cell with continual laser treatment
Bottom: Associated photoluminescence images

Sunrise mc-Si PERC cells
Best published stability – Re-fire and laser

Type 2 defect appears to be mitigated

C. Chan et al., “Rapid stabilization of HP mc-Si PERC cells” JPV 2016
Best published stability – Re-fire and laser
Best published stability – Re-fire and laser

Zoom in on y-axis shows gradual decline as type 2 defect appears:
Dark annealing can accelerate the evolution of the degradation

- 8 identical sister mc-Si PERC cells
- Each dark annealed at a different temperature for 2.5 hours, then light soaked at standard 75 °C 1kW/m²
- Dark annealing first accelerates type 1 defect forming and recovering
- Eventually, the dark annealing eliminates the type 1 defect, and only the type 2 defect remains

→ Dark annealing can be used as an accelerated test for future Type 2 degradation

[UNSW unpublished]
Standard light-soaking is not suitable

Treated cell appears to be LID free

Accelerated ageing of treated cell

Graph showing normalized effective lifetime against light soaking time (mins) with different treatments and controls.
Accelerated testing on “LID free” modules

- Accelerated by 150 °C dark anneal for 10 hours prior to light soaking
Dark anneal & Light Soak
Accelerated testing on “LID free” modules
Cell 3

Δ Voc (mV )

-13
-10
-7
-4
-1
Δ Voc Cell 1
Δ Voc Cell 2
Δ Voc Cell 3

As purchased
Dark annealed
Light soaking
Still degrading!

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Identification of the defect causing LID in mc-Si PERC

- Defect takes on 2 forms: type 1 and type 2
- 2 energy levels in band-gap make its behaviour confusing
- Unique approach to H charge state control fixes defects
- Can be added to any wafer
- Present in Cz
- Common in n-type material
- Damages bulk lifetimes
- Damages AlOx passivation

![Graph showing change in Voc over light soak time at 70 °C](image)
Greatest opportunity is with multicrystalline silicon

- Large range of types of defects
  - Crystallographic defects e.g. grain boundaries, dislocations etc
  - Contaminants
  - Variability across wafers and between wafers
- LID has major impact
- PERC cells >20% efficiency if not for LID
- Large range of defects makes H passivation more complicated but also increases its importance
Progressive improvement through repeated Hydrogenation

Progressive Hydrogenation

Cell efficiency improved from 15.4% to 18.5%

Progressive photoluminescence images (open circuit) for cells progressively hydrogenated
Advanced hydrogenation solves Rs and LID in multi

• Solutions will be published in 2017
• Consortium of 20 companies funding & commercialising the technology
• Industry partners like more patents
• Strong patent portfolio

Advanced hydrogenation of silicon solar cells
US 9190556 B2

CLAIMS

The invention claimed is:

1. A method of processing silicon, with a hydrogen source present, for use in the fabrication of a photovoltaic device having at least one rectifying junction, the method comprising heating at least a region of the device to at least 100° C. while simultaneously illuminating at least some of the device with at least one light source whereby the cumulative power of all the incident photons with sufficient energy to generate electron hole pairs within the silicon is at least 20 mW/cm².
6 new patents for manipulating H and the H charge state

• Autogeneration of H0 for enhanced hydrogen passivation
• Controlling the location of hydrogen within silicon
• Enhanced generation of H0 in n-type silicon
• Novel thermal manipulation of hydrogen
• Use of hydrogen sinks to control hydrogen flow
• Solving LID in multicrystalline silicon wafers
Summary

• Hydrogen passivation is greatly enhanced through control of the H charge state to improve diffusivity and reactivity

• Large consortium of industry partners supporting the work

• Key patents awarded

• Commercial tools now available

• It appears most defect types can be passivated

• B-O related LID rapidly mitigated - 8 sec for full recovery

• Defect X causing LID in mc-Si has been identified

• Defect X also relevant to mono and needs different hydrogen passivation process
Thank you
Thank you