p-PERT Bifacial Solar Cell Technology
Past and Future

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1. Bifacial p-PERT industrial history in brief
2. Bifacial p-PERT technology
3. Solaround achievements
4. Conclusion
1. Bifacial p-PERT industrial history in brief
BIFACIAL p-(P)ERT for SPACE: Kvant, Russia

- p-Si: radiation resistance better than in n-Si
- Thermally doped emitter and implanted back p+ layer
- No front and back texturing
- No front and back passivation but ZnS ARC
- Ti-Pd-Ag evaporated contacts
- $\eta$ (AMO) = 15-18 %

- Production p-type started in 1958
- Bifacial development started in 1964
- First bifacial satellite in 1974
- Less than 1MW/ year
Production started in 1992 at Krasnodar

Annual production 2MW/year

5” cells with Boron BSF prepared by spin-on boron glass prior to high temperature drive-in

Bifaciality factor : 70 %

Front efficiency: 16.5%

Test site: Berlin 2003

6kW on the roof of the ITC, OWZ

3kwp mono-facial and 3kWp bifacial

Albedo: 025  Annual Gain : 8 %
FIRST INDUSTRIAL BIFACIAL p-PERT: bSolar, Israel/Germany

- Production started in 2010 at Heilbronn, converting a closed production line of PERT cell with Al-BSF into a PERT line with B-BSF
- Annual production 30MW/year
- 6” cells with Boron BSF prepared by spin-on boron glass prior to high temperature drive-in but cell process different from previous (S-W)
- Bifaciality factor > 78%
- Front efficiency > 18.5%
- Stopped operating in 2012, together with most of German PV plants

Test site in Adlershof-Berlin 2011
- 27 bSolar panels + 9 reference ones
- bSolar vs. Solon modules
- Ground reflectance (Albedo): ~30%
- NS distance = 2.35m/3.5m
- Height (panel lower edge): 0.5m
### RECENTLY PUBLISHED LIST OF BIFACIAL TECHNOLOGIES (2016)

#### Table 1

<table>
<thead>
<tr>
<th>Description</th>
<th>Concentration (Sun)</th>
<th>Efficiency (front or front/rear)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buried† (independently confirmed)</td>
<td>1</td>
<td>21.9</td>
<td>[80]</td>
</tr>
<tr>
<td>Fz-Si p-type triode structure (independently confirmed)</td>
<td>1</td>
<td>21.3, 19.8</td>
<td>[81]</td>
</tr>
<tr>
<td>Fz-Si (α-Si:H rear surface passivation) (independently confirmed)</td>
<td>1</td>
<td>20.1</td>
<td>[56]</td>
</tr>
<tr>
<td>Fz-Si (independently confirmed)</td>
<td>1</td>
<td>19.4, 16.5</td>
<td>[82]</td>
</tr>
<tr>
<td>Fz-Si symmetrical (independently confirmed)</td>
<td>1</td>
<td>18.4, 18.1</td>
<td>[82]</td>
</tr>
<tr>
<td>MISIL (independently confirmed)</td>
<td>1</td>
<td>17.1</td>
<td>[83]</td>
</tr>
<tr>
<td>Flexible c-Si (thickness: 110 μm, AM0†) (independently confirmed)</td>
<td>1</td>
<td>14.7</td>
<td>[81]</td>
</tr>
<tr>
<td>GeTe (Cu,Te back contact, 40–60% transmission) (independently confirmed)</td>
<td>1</td>
<td>13.9</td>
<td>[66]</td>
</tr>
<tr>
<td>Si-HIT cell on commercial CZ c-Si 6° wafer using busbar-less front side metallization</td>
<td>1</td>
<td>23.14</td>
<td>[42]</td>
</tr>
<tr>
<td>GaAs thin film (thickness: 5 μm)</td>
<td>1</td>
<td>22.6, 12.9</td>
<td>[71]</td>
</tr>
<tr>
<td>Zebra (n-type c-Si)</td>
<td>1</td>
<td>21.3</td>
<td>[84]</td>
</tr>
<tr>
<td>nPERT</td>
<td>1</td>
<td>20.6</td>
<td>[85]</td>
</tr>
<tr>
<td>n-type HIT screen printed</td>
<td>1</td>
<td>20.2</td>
<td>[86]</td>
</tr>
<tr>
<td>Silver* solar cell</td>
<td>1</td>
<td>19.4</td>
<td>[22]</td>
</tr>
<tr>
<td>Remote plasma CVD</td>
<td>1</td>
<td>&gt; 18/&gt; 18</td>
<td>[87]</td>
</tr>
<tr>
<td>(ITO)/(p + n +)*Cz-Si/(ITO) Cu contact 25×25 mm²</td>
<td>3</td>
<td>17.9/170</td>
<td>[38]</td>
</tr>
<tr>
<td>(ITO)/(p + n +)*Cz-Si/(ITO) Cu contact 25×25 mm²</td>
<td>3</td>
<td>17.6/16.7</td>
<td>[38]</td>
</tr>
<tr>
<td>Cz-Si p-type SiNx PECVD and screen printed, industrial process</td>
<td>1</td>
<td>15.6, 128</td>
<td>[5]</td>
</tr>
<tr>
<td>p + n + *</td>
<td>7</td>
<td>15.4/13.6</td>
<td>[88]</td>
</tr>
<tr>
<td>p + n + *</td>
<td>1</td>
<td>15.7/13.6</td>
<td>[88]</td>
</tr>
<tr>
<td>GaAs thin film (thickness: 1.5 μm, AM0)</td>
<td>1</td>
<td>15.4</td>
<td>[89]</td>
</tr>
<tr>
<td>GGS</td>
<td>1</td>
<td>15.2</td>
<td>[70]</td>
</tr>
<tr>
<td>POWER cell (16% transparency)</td>
<td>1</td>
<td>12.9</td>
<td>[90]</td>
</tr>
<tr>
<td>GTe/CdTe (ITO back contact)</td>
<td>1</td>
<td>10.3/2.1</td>
<td>[74]</td>
</tr>
<tr>
<td>Flexible dye-sensitized (if 90° bending: –6%)</td>
<td>1</td>
<td>6.8</td>
<td>[65]</td>
</tr>
<tr>
<td>Dye-sensitized (Ti foil based flexible)</td>
<td>1</td>
<td>6.55/4.79</td>
<td>[66]</td>
</tr>
<tr>
<td>Dye-sensitized (polyepyrrole counter electrode)</td>
<td>1</td>
<td>5.74/3.06</td>
<td>[67]</td>
</tr>
<tr>
<td>Ultra-thin CdTe (0.68 μm)</td>
<td>1</td>
<td>5.7/5.0</td>
<td>[69]</td>
</tr>
<tr>
<td>Solid-state dye-sensitized solar cell (tandem - no color distortion)</td>
<td>1</td>
<td>3.3</td>
<td>[18]</td>
</tr>
<tr>
<td>Organic (50% transparency)</td>
<td>1</td>
<td>3.24</td>
<td>[91]</td>
</tr>
<tr>
<td>Simulated n-type HIT</td>
<td>1</td>
<td>27.02</td>
<td>[24]</td>
</tr>
</tbody>
</table>

* Not under standard test conditions.


400 papers screened on bifacial cells

One p-PERT only in the list

[SolAround]
MOTIVATION

- p-type mainstream monocrystalline silicon
- PERT structure with full Boron BSF and passivated back is intrinsically superior to local BSF or full passivated structures.
- Highest front efficiency
- Maximum bifaciality

SOLUTION: p-PERT CELL

- THE NOVELTY: New Boron Controlled Doping technology using surface deposited layer
- SolAround’s solution provides also Boron doping process without degradation of the bulk lifetime
2. Bifacial p-PERT technology
p-SI PERT CELL CONCEPTS

**Conventional p-type mono-facial cell**
- Phosphorus doped emitter
- p-type Cz-Si
- Al-BSF
- Al-contact
- AgAl-pad

**SolAround PERT p-type bifacial cell**
- Phosphorus doped emitter
- p-type Cz-Si
- Boron-BSF

**Aluminum BSF**
- Opaque back side, prevents bifaciality
- Limits increase of front efficiency

**Boron BSF**
- Improved front efficiency due to superior BSF (higher B solubility)
- Improved optical properties
- Open back side, allows bifaciality
- Drawback: potential “lifetime killer”
COMPARISON OF AI-BSF VERSUS BORON-BSF

INTRINSIC FACTORS OF FRONT EFFICIENCY IMPROVEMENTS OF A BIFACIAL COMPARED to MONO FACIAL CELL

Light trapping and recombination improvements

\[ R_{\text{in}}^{b} = 60 \% \]
\[ \text{Al solubility in Si } \approx 3 \times 10^{18} \text{ cm}^{-3} \]
\[ S_{\text{eff}} = 400 \div 1000 \text{ cm/s} \]

\[ R_{\text{in}}^{b} = 76 \pm 5 \% \]
\[ \text{B solubility in Si } > 10^{20} \text{ cm}^{-3} \]
\[ S_{\text{eff}} < 10 \text{ cm/s} \]
PARAMETER REQUIREMENTS FOR n⁺-p-p⁺ PERT (BIFACIAL) CELL

Electro-Physical Parameters:
- High bulk diffusion length $L >> d$ ($d$: cell thickness $\sim$200 microns)
- High potential of back high-low barrier (BSF)
- Low effective back surface recombination ($S_{eff}$), at least one order of magnitude less than in Al-BSF i.e. less than 10 cm/s.

Optical Parameters:
- Effective light trapping in photoactive wavelength region
- Light rejection in non-photoactive wavelength region
NECESSARY ACTIONS FOR ACHIEVING OBJECTIVES

- Use starting Si with high lifetime $\tau$
- Retain $\tau$ during cell fabrication
- Proper $p^+$ layer doping
- Proper pyramid textured on front
- No texturization on boron doped (back) side
EXPECTED FRONT EFFICIENCY FOR BIFACIAL CELL WITH B-BSF

Solarround technology with:
- Controlled B doping
- Back surface passivation
- 3% contacting surface and floating busbar

bSolar industrial technology
- 7.2 % contact coverage

\[ \tau = 0.5 \text{ ms} \]
3. Solaround achievements
BORON DOPING OF \( p^+ \) LAYER

Over doping
(first generation solar cell)

Controllable doping
(new generation solar cell)
PRELIMINARY RESULTS WITH NEW BORON BSF PROCESS

Implied open circuit voltage, \(iV_{oc}\),
(of \(n^*-p-p^*\) structures vs. doping level of a \(p^+\) layer)

<table>
<thead>
<tr>
<th>(R_{\text{sheet}}, \Omega/\square)</th>
<th>68</th>
<th>82</th>
<th>102</th>
<th>118</th>
<th>140</th>
</tr>
</thead>
<tbody>
<tr>
<td>(J_0, \text{fA/cm}^2)</td>
<td>42</td>
<td>58</td>
<td>36</td>
<td>42</td>
<td>34</td>
</tr>
</tbody>
</table>
SOLAROUND CELL BIFACIALITY

Front IQE

Back IQE
SOLAROUND BIFACIAL CELL PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
<th>Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{sc}$ mA/cm$^2$</td>
<td>39.2 – 39.5</td>
<td>&gt;40</td>
</tr>
<tr>
<td>$V_{oc}$ mV</td>
<td>650-658</td>
<td>&gt;660</td>
</tr>
<tr>
<td>FF, %</td>
<td>78-79</td>
<td>&gt;80</td>
</tr>
<tr>
<td>Eff (front), %</td>
<td>19.9 - 20.3</td>
<td>&gt;21</td>
</tr>
<tr>
<td>$I_{sc f}$ / $I_{sc}$, %</td>
<td>89-92</td>
<td>&gt;92</td>
</tr>
</tbody>
</table>
4. Conclusions
- \( n^+\text{-p-p}^+ \) with a uniformly B doped \( p^+ \) layer is a promising structure for industrially produced PERT bifacial cells.

- B diffusion using preliminary deposited B containing solid layer allows controllable doping of \( p^+ \) layer.

- Retained high bulk lifetime, low back \( S_{\text{eff}} \) and high quality emitter provide implied \( V_{\text{oc}} \) of the PERT structure exceeding 700mV enabling high front efficiency in the range 21-22%.

- **High bifaciality factor:** Back to front short circuit current ratio is in the range 89-92%.

- High quality Cz starting \( p \)-Si can compete with \( n \)-Si as material for cell production with front efficiency above 22%.
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