Amorphous silicon/crystalline silicon heterojunctions:
The future of high-efficiency silicon solar cells

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The importance of efficiency

Goodrich et al., NREL/PR-6A20-50955 (2011).
Record efficiencies

Multijunction Cells (2-terminal, monolithic)

- Three-junction (concentrator)
- Three-junction (non-concentrator)
- Two-junction (concentrator)
- Two-junction (non-concentrator)
- Four-junction or more (non-concentrator)

Thin-Film Technologies

- Cu(In,Ga)Se_2
- CdTe
- Amorphous Si:H (stabilized)
- Nano-, micro-, poly-Si
- Multijunction polycrystalline

Emerging PV

- Dye-sensitized cells
- Organic cells (various types)
- Organic tandem cells
- Inorganic cells
- Quantum dot cells

Single-Junction GaAs

- Single crystal
- Concentrator
- Thin-film crystal

Crystalline Si Cells

- Single crystal
- Multicrystalline
- Thick Si film
- Silicon Heterostructures (HIT)
- Thin-film crystal

Efficiency (%)
Record efficiencies

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Efficiency (%)
Record efficiencies
Diffused-junction solar cells

- Front passivation is insulating; contact is made to the emitter by “spiking” the Ag through the passivation layer.
- Poor passivation at front and rear contacts limits $V_{oc}$ to ~650 mV.
Silicon heterojunction solar cells

- $a$-Si:H provides excellent passivation of c-Si surface
- Charge can trickle through $a$-Si:H layers; recombination-active contacts are displaced from c-Si surface
$V_{oc}$ and silicon heterojunction solar cells

- Lifetime > 1 ms; $V_{oc} > 730$ mV
- Excellent $V_{oc}$ is trademark of heterojunctions

Descoeudres et al., IEEE JPV 3, 83 (2013).
Getting to S-Q: $V_{oc}$

- For 100-µm-thick $c$-Si wafer, S-Q predicts $V_{oc, max} = 760-770$ mV
- Commercially available $c$-Si cells: $V_{oc} \approx 650$ mV
- Record-efficiency PERL $c$-Si cell: $V_{oc} = 706$ mV
- Sanyo Si heterojunction cell: $V_{oc} = 750$ mV!

$V_{oc}$: What next?

- Increase $V_{oc}$ by squeezing more charge into a smaller volume
- Can’t reduce recombination further, but can thin wafer, which helps because generation is mostly at the front

$V_{oc}$: What next?

- Surface recombination gains importance as wafer is thinned.
- $V_{oc}$ improves with decreasing wafer thickness for surface recombination velocities < 100 cm/s.
- Silicon heterojunctions best technology for thin wafers.

![Graph showing the relationship between $V_{oc}$ and wafer thickness for different bulk lifetimes.](graph.png)

- For $\tau_{bulk} = 0.1$ ms, $V_{oc}$ decreases with decreasing wafer thickness.
- For $\tau_{bulk} = 1$ ms, $V_{oc}$ remains relatively constant.
- For $\tau_{bulk} = 10$ ms, $V_{oc}$ increases with decreasing wafer thickness.

Graph parameters:
- $s_f = s_b = 1$ cm/s
- $\tau_{bulk} = 0.1$ ms
- $\tau_{bulk} = 1$ ms
- $\tau_{bulk} = 10$ ms

Graph scale:
- $V_{oc}$ (V) range: 0.56 to 0.74
- Wafer thickness (um) range: 50 to 200

Graph units:
- 100 cm/s
- 10 cm/s
- 1000 cm/s
Record-high $V_{oc}$s, but... low $J_{sc}$ and $FF$

**IMT heterojunction**
- $V_{oc} = 727$ mV
- $J_{sc} = 38.9$ mA/cm$^2$
- FF = 78.4%
- Eff. = 22.1%

**UNSW PERL**
- $V_{oc} = 706$ mV
- $J_{sc} = 42.7$ mA/cm$^2$
- FF = 82.8%
- Eff. = 25.0%

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Where does the light go?

100-μm-thick wafer; 20.8%

Holman et al., *IEEE JPV* (submitted).
Where does the light go?

- Reflection from Ag grid and TCO anti-reflection coating
- UV and blue parasitic absorption in front a-Si:H layers
- UV and IR parasitic absorption in front TCO; IR parasitic absorption in rear TCO
- Incomplete trapping of IR light
UV and blue parasitic absorption
Parasitic absorption in the front a-Si:H layers

- All light absorbed in a-Si:H p-layer is lost
- 70% of light absorbed in a-Si:H i-layer is lost
- UV loss in TCO is small (0.2 mA/cm²)
Thinner layers?

- Current decreases with $p$-layer thickness, but FF improves
- Overall trend is in favor of $J_{sc}$

- Current decreases with $i$-layer thickness, but $V_{oc}$ improves
- $i$-layer should be thick enough to provide passivation, but no thicker
More transparent materials?

- n and k both decrease as CO₂ is added to plasma: \(a\)-Si:H → \(a\)-SiOₓ
- FF falls very rapidly
- \(\mu c\)-Si has lower k than \(a\)-Si:H
- Growth is substrate dependent: hard to grow thin, highly crystalline layers on, e.g., \(a\)-Si:H
IR parasitic absorption

Holman et al., JAP. 113, 013107 (2013).
Holman et al., SolMat. (in press).
Holman et al., Light (submitted).
Holman et al., IEEE JPV (submitted).
Parasitic absorption reduces both EQE and R

$R_{\text{sub}}$ (i.e., $R @ \lambda=1200 \text{ nm}$) is metric of IR parasitic absorption that can be measured on insulating test structures.
IR parasitic absorption
High-mobility hydrogen-doped indium oxide (IO:H)

- Replace front ITO with high-mobility IO:H ($\mu > 100 \text{ cm}^2/\text{Vs}$)
- Less (parasitic) free-carrier absorption for equivalent sheet resistance
- An ultrathin ITO layer is still required for good contact to screen-printed Ag fingers

Koida et al., several papers between 2007-2013.
Optimized rear TCO layers

- Ideal rear TCO layer is very transparent (to avoid FCA in the TCO), and ...
- >150 nm thick (to suppress plasmon excitation in the metal reflector)
Record cells

<table>
<thead>
<tr>
<th></th>
<th>$n$-type</th>
<th>$p$-type</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>area [cm$^2$]</strong></td>
<td>3.98</td>
<td>3.98</td>
</tr>
<tr>
<td><strong>$V_{oc}$ [mV]</strong></td>
<td>727</td>
<td>722</td>
</tr>
<tr>
<td><strong>$J_{sc}$ [mA/cm$^2$]</strong></td>
<td>38.9</td>
<td>38.4</td>
</tr>
<tr>
<td><strong>FF [%]</strong></td>
<td>78.4</td>
<td>77.1</td>
</tr>
<tr>
<td><strong>efficiency [%]</strong></td>
<td>22.14</td>
<td>21.38</td>
</tr>
</tbody>
</table>
Adding a low-refractive-index rear dielectric layer

For a 300-nm-thick layer of air ($n_d = 1$), only 4% of incident light is absorbed in the Ag layer ($r_f = 99.8\%$)
Really Rockin’ Rear Reflector (RRRR)
It’s really rockin’…but the old reflector was already very good. In industry, probably not worth the cost of the extra processing step.
RRRR and CheapRRRR performance

Best rear reflector ever?
Summary

- $a$-Si:H provides excellent surface passivation and charge extraction; recombination-active metal contacts are removed from the wafer surface
- Heterojunction design enables $V_{oc} > 730$ mV; further improvements only if wafer is thinned
- But...heterojunction design compromises $FF$, $J_{sc}$
- Reduce blue parasitic absorption in $a$-Si:H layers with thin layers, transparent materials, back-contacted design, or downshifters
- Reduce IR parasitic absorption with high-mobility TCOs, and “detached” rear metal reflector

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