Solar Energy

A Journey with the Global Climate and Energy Project From 2003 to Now

Mike McGehee

Material Science and Engineering
Solar Energy is Booming as Costs have Plummeted!

We have passed a tipping point on addressing climate change.

Graph: Earth Energy Policy Institute/Bloomberg
The value of higher efficiency

• For utility scale installations an extra efficiency point is worth $0.03/W.

• 25 %-efficient panels can be sold for > $0.70/W.
The need for less expensive factories

Perovskites

Generic formula: $\text{ABX}_3$, where $X =$ oxygen or halide

A cation 12-fold, B-cation 6-fold co-ordinated with $X$ anion

$\text{CH}_3\text{NH}_3^+ \quad \text{Pb}^{2+} \quad \text{I}^-$

$\text{CH}_3\text{NH}_3\text{PbI}_3$

*Methylammonium-lead-iodide*
Figure 4. Costs by component for CdTe modules. Source: Internal NREL bottom-up costs analysis.

Jones-Albertus, Woodhouse et al, Prog. in PV: Research and Apps, DOI: 10.1002/pip.2755
Tuning the composition adjusts the band gap

$\text{CH}_3\text{NH}_3\text{PbI}_3$
$E_g = 1.6 \text{ eV}$

$(\text{MA})\text{Pb(Br}_x\text{I}_{1-x})_3$

$\text{CH}_3\text{NH}_3\text{PbBr}_3$
$E_g = 2.3 \text{ eV}$

$\text{CH(NH}_2\text{)}_2\text{PbI}_3$
$E_g = 1.48 \text{ eV}$

$\text{CH(NH}_2\text{)}_2\text{Pb(Br}_x\text{I}_{1-x})_3$

$\text{CH(NH}_2\text{)}_2\text{PbBr}_3$
$E_g = 2.2 \text{ eV}$

Tandem Solar Cells are the Best Way to Raise Efficiency

Epitaxially Grown Single Crystal III-V Tandem
46% efficient
>$40,000/m²

Perovskite on Conventional Silicon Tandem
Up to 33% efficient
<$105/m²

Image: US Naval Research Lab

Stanford University
Tandem Architectures

**Mechanically-stacked**
- Easier prototyping
- No current matching required
- No changes to the Si cell
- World record: 25.2 % (EPFL)

**Monolithically-integrated**
- Fewer layers that parasitically absorb
- World record: 23.6 % (Stanford-ASU)

Voltage matching is also possible.
## Selecting the high band gap semiconductor

<table>
<thead>
<tr>
<th>Eg</th>
<th>Material(s)</th>
<th>Device efficiency</th>
<th>Stable to phase segregation</th>
<th>Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5eV</td>
<td>FAPbI$_3$ (FAPbI$<em>3$)$</em>{0.85}$(MAPbBr$<em>3$)$</em>{0.15}$</td>
<td>20.2% 17.3%</td>
<td>Yes ?</td>
<td>Seok Seok</td>
</tr>
<tr>
<td>1.6eV</td>
<td>MAPbI$<em>3$ FA$</em>{0.9}$Cs$_{0.1}$PbI$_3$ Triple cation*</td>
<td>19.7% 16.5% 21.1%</td>
<td>Yes ?</td>
<td>Park Grätzel</td>
</tr>
<tr>
<td>1.7eV</td>
<td>FA$<em>{0.83}$Cs$</em>{0.17}$(I$<em>{0.6}$Br$</em>{0.4}$)$<em>3$ MAPbBr$</em>{0.8}$I$_{2.2}$</td>
<td>17% 14.9%</td>
<td>Possibly No</td>
<td>Snaith Huang</td>
</tr>
<tr>
<td>1.8eV</td>
<td>MAPbBr$<em>{0.9}$I$</em>{2.1}$</td>
<td>12.7%</td>
<td>No</td>
<td>Zou</td>
</tr>
<tr>
<td>1.9eV</td>
<td>CsPbBrI$_2$</td>
<td>6.5%</td>
<td>Yes</td>
<td>McGehee Snaith</td>
</tr>
<tr>
<td>2.3eV</td>
<td>MAPbBr$_3$ CsPbBr$_3$</td>
<td>8.7% 6.5%</td>
<td>Yes</td>
<td>Green Cahen</td>
</tr>
</tbody>
</table>
Cs$_{0.17}$FA$_{0.83}$Pb(Br$_{0.17}$I$_{0.83}$)$_3$ perovskite on heterojunction Si tandem

1cm$^2$
23.6 % efficiency certified by NREL

Heterojunction silicon from Zach Holman’s team at ASU

Kevin Bush, Alex Palmstrom et al.
Perovskite-perovskite tandems

Giles E. Eperon, Tomas Leijtens, Michael D. McGehee and Henry J. Snaith et al., Science DOI: 10.1126/science.aaf9717
Using tin allows us to reach 1.22 eV bandgap

Giles E. Eperon, Tomas Leijtens, Michael D. McGehee and Henry J. Snaith et al., Science DOI: 10.1126/science.aaf9717
Monolithic two-terminal tandem

- Need to make the low gap layer thicker
- Need a better 1.8 eV semiconductor
- 25% efficiency should be possible in the next 1-2 years
1.2 eV

Rear subcell (narrow gap)

ITO glass

1.6 eV

Front subcell (wide gap)

ITO glass

4-Terminal Tandem

4 % efficiency

16 % efficiency

20 % efficiency

Completely stable over 20 hours of testing
3 steps to greatly improving stability

1. Replace metal electrodes with indium tin oxide
2. Avoid methylammonium cations
3. Package the cells just the way PV companies do
Improved thermal and environmental stability with sputtered ITO electrode

A MAPbI$_3$ cell after heating at 100 degrees C in air.

2nd strategy for improving thermal stability

Mixtures of cesium and formamidinium make compounds that are stable well above 100 degrees C.
Packaging devices

- Solar glass (3.2mm, Pilkington)
- Edge seal (Butyl, Quanex)
- Encapsulants (EVA or Surlyn)
Testing of Fully Encapsulated Devices in 85°C/85% RH Damp Heat

Encapsulant A: EVA
Encapsulant B: Surlyn

This test is very aggressive. Panels that pass it will usually not fail due to heat and humidity over 25 years outside.
Outlook on stability

• Using the more stable perovskites, impermeable and unreactive electrodes and proper packaging has improved stability enormously.

• We have passed a temperature cycling test also.

• Long-term testing under light is underway. 1000 hour tests are encouraging.
Outlook on efficiency

• Single junction efficiencies approaching 25 % seem possible.

• Band gaps for single and multijunction tandems are available.

• Breaking 25 % efficiency with tandems is inevitable and 30 % look achievable.
Perovskite companies

<table>
<thead>
<tr>
<th>Company</th>
<th>Location</th>
<th>Approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxford PV</td>
<td>England</td>
<td>Perovskite on Si monolithic 2T tandem</td>
</tr>
<tr>
<td>Iris PV</td>
<td>Silicon Valley</td>
<td>Perovskite mechanically stacked on Si Tandem</td>
</tr>
<tr>
<td>Hunt Energy</td>
<td>Dallas, Texas</td>
<td>Single junction perovskites</td>
</tr>
<tr>
<td>Saule</td>
<td>Poland</td>
<td>Flexible perovskite cells</td>
</tr>
<tr>
<td>Weihua Solar</td>
<td>China</td>
<td>Printed single junction panels</td>
</tr>
</tbody>
</table>
Companies founded by alumnae

- Thin Silicon
- Allion (printing solar cells and using robotics to install them)
- One Earth Capital (venture capital firm)
- PLANT PV (tandem solar cells and inks for electrodes)
- Plotly (scientific plotting)
- Sinovia (silver nanowire transparent electrodes)
- Dfly (electronics for making systems of solar modules more efficient)
- NextTint (smart windows)
- WellDone Technology (monitoring of water pumps in remote Africa)
- CelLink (improved method for assembling solar modules)
- Iris PV (perovskite-silicon tandem solar cells)

GCEP created the environment from which the companies sprung!
Acknowledgments

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• Ye Chen, Wei Wang, Wen Ma, Farhad Moghadam (Sunpreme)
• Hema Karunadasa and her group
• Mike Toney and his group
• Duncan Hargrave (D2 solar)
• Homer Antoniadis, Daniel Inns (DuPont)
• Jonathan Mailoa, Robert Hoye, Tomas Leijtens, Sarah Sofia, Tonio Buonassisi (MIT)
• David McMeeking and Henry Snaith (Oxford)

Global Climate and Energy Project
What are the implications of Pb being toxic?

Amount of lead

• The panels will have about 1 g of lead in the perovskite.

• Silicon panels typically have 16 g of lead in the solder.

• Lead would not easily escape a packaged module.
First Monolithic Perovskite/Silicon Tandem – 13.7% with 11.5mA/cm²

- Significant parasitic absorption in the hole transport material – Spiro-OMeTAD

Current World Record Mechanically Stacked Perovskite on Si Tandem

Figure 2. 4-terminal mechanically stacked tandem: (a) schematic drawing of the tandem stack with a NIR-transparent perovskite top cell illuminated through the glass substrate (superstrate configuration) and a silicon heterojunction bottom cell; (b) EQE spectra and (c) J–V characteristics of the mechanically stacked perovskite/SHJ tandem measurement with a 0.25 cm$^2$ top cell and 25.2% total efficiency.