Emerging Materials and Devices: Metal Halide Perovskites
Silicon – powering the world today

Winning since 1954 - can anything be better?
Perovskites: from 1892 to 2009

ABX$_3$ Crystal Structure

Solar energy conversion:
Prof Tsutomu Miyasaka et al.

Discovery: 1892

Prof. Tsutomu Miyasaka et al.

Over die Cäsium- und Kalium-Bleihalogenide.

Von

H. L. Wells.


\[
\begin{align*}
\text{Cs}_4\text{PbCl}_6 & \quad \text{Cs}_4\text{PbBr}_6 & \quad \text{Cs}_4\text{PbI}_6 \\
\text{Cs}_3\text{PbCl}_8 & \quad \text{Cs}_3\text{PbBr}_8 & \quad \text{Cs}_3\text{PbI}_8 \\
\text{Cs}_2\text{Pb}_2\text{Cl}_6 & \quad \text{Cs}_2\text{Pb}_2\text{Br}_6 & \quad \text{Cs}_2\text{Pb}_2\text{I}_6
\end{align*}
\]

Sheffield Scientific School, New Haven, Conn., Oktober 1892.
Our starting point in 2010

Cooperative research programme

Takurou Murakami’s Notes for Mike Lee
Two disparate “tribal” fields of research (pre-perovskites)

“Traditional” PV:
Silicon and thin-film

Emerging PV:
Organic, dye-sensitized and nanostructured PV

Based on interpenetrating networks on electron and hole conducting materials – required to separate tightly bound excitons and transport electron and holes in highly disordered materials.
Are perovskites best when porous or crystalline?
The n-i-p “planar” heterojunction

Surprise discovery:

• No efforts for passivation - Benign defects
• Long carrier lifetimes
• High charge carrier mobility
• Very high radiative efficiency
The n-i-p “planar” heterojunction

![Diagram showing energy levels for p-type, Perovskite (intrinsic), and n-type materials.](image-url)
Surging Efficiency

- Best Silicon: 26%
- Mainstream Commercial Silicon: 22.5%
- Perovskites: 10.9%

Graph showing the efficiency improvements from 1970 to 2020.
How Can We Extract More Energy From Sun Light?

The “tandem” concept
Perovskite-on-silicon tandems

- **Perovskite cell**: Very high voltage wide band gap top cell
- **Silicon cell**: Compatible with a range of Si rear cells

- Efficiency: Presently >29%
- Near Future: 32 to 34%
## Companies active in perovskite R&D

<table>
<thead>
<tr>
<th>Company</th>
<th>Target technology</th>
<th>URL</th>
<th>Country of origin/activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxford PV</td>
<td>Perovskite-on-silicon tandem</td>
<td><a href="http://www.oxfordpv.com">www.oxfordpv.com</a></td>
<td>UK, Germany</td>
</tr>
<tr>
<td>SwiftSolar</td>
<td>Thin-film lightweight all-perovskite tandems</td>
<td><a href="http://www.swiftsolar.com">www.swiftsolar.com</a></td>
<td>USA</td>
</tr>
<tr>
<td>Hunt Perovskite Technologies</td>
<td>Monolithic thin-film</td>
<td><a href="http://www.huntperovskite.com">www.huntperovskite.com</a></td>
<td>USA</td>
</tr>
<tr>
<td>Saule Technologies</td>
<td>Flexible, lightweight perovskite</td>
<td><a href="http://www.sauletech.com">www.sauletech.com</a></td>
<td>Poland</td>
</tr>
<tr>
<td>GCL</td>
<td>Rigid monolithic, silicon tandem</td>
<td><a href="http://www.en.gcl-power.com">www.en.gcl-power.com</a></td>
<td>China</td>
</tr>
<tr>
<td>MicroQuanta</td>
<td>Rigid monolithic</td>
<td><a href="http://www.microquanta.com">www.microquanta.com</a></td>
<td>China</td>
</tr>
<tr>
<td>Tandem PV</td>
<td>4T or mechanically stacked tandem</td>
<td><a href="http://www.tandempv.com">www.tandempv.com</a></td>
<td>USA</td>
</tr>
</tbody>
</table>
# Companies active in perovskite R&D

<table>
<thead>
<tr>
<th>Company</th>
<th>Target technology</th>
<th>URL</th>
<th>Country of origin/activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOSHIBA</td>
<td>Thin-film modules</td>
<td><a href="https://www.toshiba.co.jp/">https://www.toshiba.co.jp/</a></td>
<td>Japan</td>
</tr>
<tr>
<td>SOLAR-TECTIC</td>
<td>Perovskite silicon tandem</td>
<td><a href="http://www.solartecticllc.com">http://www.solartecticllc.com</a></td>
<td>USA</td>
</tr>
<tr>
<td>SHARP</td>
<td>Thin film modules, Tandem?</td>
<td><a href="https://global.sharp/">https://global.sharp/</a></td>
<td>Japan</td>
</tr>
<tr>
<td>MITSUBISHI CHEMICAL</td>
<td>Flexible modules</td>
<td><a href="https://www.m-chemical.co.jp/en/">https://www.m-chemical.co.jp/en/</a></td>
<td>Japan</td>
</tr>
</tbody>
</table>
Moving into volume manufacturing

2019
Low volume production

2019 / 2020
Scale up

2021
Volume manufacturing
Roadmap to high volume manufacturing

>100 MW production during 2021 then to GW scale and beyond....
Where to go beyond 2 junctions?

3- Junctions!

Triple Junction “All-perovskite” thin-film
Potential for 37% efficiency

Open-circuit voltage ~ 2.83V

D. McMeekin et al. 2019 Joule

Triple Junction “perovskite-perovskite-silicon”
Potential for 39% efficiency

Open-circuit voltage ~ 2.7 V

J. Werner et al. 2018 ACS Energy Letters
Key technical challenges underpinned by science

**Efficiency**
- Maximising Voc
- Improved charge extraction materials.
- Improved passivation
- Understanding defect chemistry
- New device concepts
  - Triple junction
  - Rear contact
  - Quantum cutting
  - Concentrator
  - Perovskite-organic tandems

**Stability**
- Understand photochemical degradation
- Understand ionic migration
- Understand the influence of additives
- Deliver absorbers stable to: light, moisture, temperature, electric field AND all combined!
- Understand degradation in the filed and its relation to lab based tests.

**New Materials**
- Improved lead-halide perovskites (new A-site cations, new doping compositions, new 2D/3D composites)
- Improved low band gap Sn-based perovskites
- New Pb-Free perovskite analogues.
Thanks to……

Collaborators:

Over 250 collaborators and co-authors, including:

Oxford:
- Michael Johnston
- Laura Herz
- Robin Nicholas
- Feliciano Giustino (now U Texas)
- Paolo Radaelli
- Moritz Reide

IIT Millan:
- A. Petrozza et al.

HZB Berlin:
- PV ComB team

Cambridge:
- RH Friend et al.

Linköping:
- Feng Gao & Sai Bai

USA:
- S. Marder et al.
- D. Ginger et al.
- M. McGehee et al.
- A-KY Jen et al.
- J. Berry et al.

EU Projects and Partners from: SANS, MESO, CHEOPS, PERTPV, PEROCUBE And ITN networks, DESTINY, Maestro and PERSEPHONE