Towards efficient and stable perovskite/silicon tandem solar cells

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Solar on Fire
As prices have dropped, installations have skyrocketed.

Solar park auction
Mexico 2017:
0.0177 $/kWh!

New installations 2018
>95 GW_p

*Estimate. Sources: Bloomberg, Earth Policy Institute, www.earth-policy.org*
Si Solar Cell Efficiency Close to Limit

Data Source: NREL & DOI: 10.1098/rsta.2011.0413

Tandem cells?

Thermodynamic limit

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Si Solar Cell Efficiency Close to Limit

The rise of perovskites

NREL efficiency chart
Towards efficient and stable perovskite/silicon tandem solar cells

- Solar cell efficiency simulations
- Ion migration in perovskites
Realistic solar cell model

• How good can perovskite/silicon solar cells be?
• How much of an advantage do they have under real-life conditions?
• Model predicts performance under real-life conditions
Three different connection schemes

Series tandem – current matching

Module tandem – voltage matching

Four-terminal tandem – electrically independent
Realistic solar cell model

Temperature, irradiance, spectrum @ two locations, Utrecht NL and Colorado
EQE & IV of solar cells

Optical model

Electrical model
different connection schemes

Total power conversion efficiency over a year
Sunpower solar cell model

SunPower C60® mono-crystalline silicon solar

$R_S = 0.7 \, \Omega \, \text{cm}^2$

$R_{SH} = 1800 \, \Omega \, \text{cm}^2$

$I_0 = 0.10 \, \text{pA/cm}^2$
Sunpower solar cell model

![Graph](image-url)

- **Current density (mA/cm²)** as a function of **Voltage (V)** for different light intensities:
  - 1000 W/m²
  - 1000 W/m², 50 °C
  - 800 W/m²
  - 500 W/m²
  - 300 W/m²

- **Efficiency (η %)** vs. **Temperature (K)**
  - Simulated record cell
  - Measured Sunpower cell
Perovskite/Silicon tandem
Realistic tandem solar cell model

- Series
- Module
- Four-terminal

η (%)

- Realistic tandem
- Si cell

STC

STC

STC
Utrecht, The Netherlands
• narrow annual temperature range
• high precipitation
• hours sunshine 1475 per year

Denver, Colorado (US)
• broad annual temperature range
• low precipitation
• hours of sunshine 3107 per year
Realistic tandem solar cell model
Low Irradiance is a problem!
Realistic tandem solar cell model
Realistic tandem solar cell model

Non-radiative recombination

Parasitic resistances

Non-radiative recombination

Parasitic resistances

Non-radiative recombination
Realistic tandem solar cell model

- **Series resistance**
- **Shunt resistance**
- **Non-rad. recombination**
- **Contact losses**
Realistic tandem solar cell model

- Optical losses
- Shunt resistance
- Series resistance
- Non-rad. recombination
- Contact losses
A bad silicon cell is improved most
Conclusion I: Solar cell model

- Tandem solar cells
  - Sensitive to environmental conditions
  - Device parameters of perovskite cells are not good enough yet
  - Tandem cells make most sense for a bad Si base cell

Moritz Futscher et al., ACS Energ. Lett. 1, 2016
Moritz Futscher et al., ACS Energ. Lett. 2, 2017
Moritz Futscher et al., ACS Energ. Lett. 3, 2018
Towards efficient and stable perovskite/silicon tandem solar cells

- Solar cell efficiency simulations
- Ion migration in perovskites
Evidence for ion migration in hybrid perovskite solar cells with minimal hysteresis

Philip Calado, Andrew M. Telford, Daniel Bryant, Xiaoe Li, Jenny Nelson, Brian C. O’Regan & Piers R.F. Barnes

Migration of cations induces reversible performance losses over day/night cycling in perovskite solar cells

Konrad Domanski, Bart Roose, Tasuku Matsui, Michael Saliba, Silver-Hamil Turren-Cruz, Juan-Pablo Correa-Baena, Cristina Roldán Carmona, Giles Richardson, Jamie M. Foster, Filippo De Angelis, James M. Ball, Annamaria Petrozza, Nicolas Mine, Mohammad K. Nazeeruddin, Wolfgang Tress, Michael Grätzel, Ulrich Steiner, Anders Hagfeldt and Antonio Abate
Perovskites are ionic semiconductors

\[ \text{MA}^+ \quad \text{Pb}^{2+} \quad \text{I}^- \]
Ion migration in MAPbI$_3$

Ion migration in MAPbI$_3$

Pb-I plane

MA-I plane

![Diagram showing ion migration in MAPbI$_3$.](image-url)
Effect of an external electric field on ion migration

(a) V=0 equilibrium

- anode
- transport layer
- transport layer
- cathode
Effect of an external electric field on ion migration

Going from (d) to (a): mobile ions drift towards the interfaces to screen the built-in electric field.
Effect of ion migration

Inverted perovskite structure

- Ag/Au
- C60/BCP
- MAPbI₃
- ITO/NiOₓ

200 nm

anode

200 nm
cathode

- Capacitance (nF/cm²)
- Frequency (Hz)

180 K - 270 K
210 K - 300 K
240 K - 330 K
Quantifying ion migration

The diagram illustrates the migration of ions over time under an applied voltage. The graph on the right shows the capacitance (nF/cm²) as a function of time (s) at 300 K. The voltage applied is 0.4 V, and the time scale is 1 s. The diagram on the left depicts the initial and final states of ion migration.
Quantifying ion migration

Transient ion-drift

\[ C(t) = \Delta C(N_{ion}) \left[ 1 - \exp \left( -\frac{t}{\tau} \right) \right] \]

\[ \tau = \frac{k_B T \epsilon}{q^2 D_0 N_A} \exp \left( \frac{E_A}{k_B T} \right) \]

Mobile ion species in MAPbI$_3$

<table>
<thead>
<tr>
<th>A1</th>
<th>C1</th>
<th>C2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Migrating ion species</td>
<td>I$^-$</td>
<td>MA$^+$</td>
</tr>
</tbody>
</table>
Quantifying ion migration in MAPbI$_3$

Solar cells fabricated at AMOLF and at the University of Konstanz with power conversion efficiencies ranging from 1 to 12%.
Conclusion I → MAPbI$_3$

- Both MA$^+$ and I$^-$ are migrating but on completely different timescales.
- The migration of MA$^+$ ions is the major factor influencing the hysteresis in MAPI solar cells.
- I$^-$ migration reproducible, MA$^+$ migration depends heavily on fabrication, degradation.
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Tandem cells!
Towards efficient and stable perovskite/silicon tandem solar cells

- Solar cell efficiency simulations
  - Need for better materials – less NR recombination

- Ion migration in perovskites
  - Less migration = more stable
  - Material development can suppress ion migration