CIGS-based Tandem Solar Cells

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Efficiency potential of Cu(In,Ga)Se$_2$ thin film solar cells

<table>
<thead>
<tr>
<th>Empa cell on PI</th>
<th>Jsc [mA/cm$^2$]</th>
<th>Voc [mV]</th>
<th>FF [%]</th>
<th>Eff [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SQ-limit (1.15 eV)</td>
<td>42.3</td>
<td>887</td>
<td>87</td>
<td>32.7</td>
</tr>
<tr>
<td>Losses compared to SQ-limit</td>
<td>-17%</td>
<td>-17%</td>
<td>-9.3%</td>
<td></td>
</tr>
</tbody>
</table>

Envisaged improvement for CIGS (maybe not all applicable on flexible substrate):
- Jsc by ~10% (38.5 mA/cm$^2$)
- Voc by ~9% (800 mV)
- FF by ~3% (81%)

$\Rightarrow$ efficiency of 25% for CIGS solar cells is a realistic goal

Development supported by HZ2020 project Sharc25 with 11 European partners
Polycrystalline thin film solar cells with efficiency >30%?

- Module efficiency is critical to reduce non-module costs


Thermodynamic losses in PV

- Energy loss in Carnot cycle
- Entropy loss in absorption or emission
- Entropy loss due to non-reciprocity

Tandem can help here

- Energy loss due to thermalization or lack of absorption
- Entropy loss due to lack of angle restriction
- Entropy loss due to incomplete light trapping and reduced QE
- Conventional single-junction solar cell

Chalcogenide and Perovskite thin film solar cells are promising for tandem devices:
- Tunable, low bandgap
- Polycrystalline, thin film absorbers on various substrates deposited in cost-effective manner
Tandem configurations

4-terminal tandem

- Both cells can operate in resp. MPP
- “simple” stacking possible
- Additional optical losses in transparent contacts
- Two DC circuits

2-terminal (monolithic) tandem

- Less optical losses in transparent contacts
- Only one DC circuit
- Current matching required for all incident angels
- Reduced energy yield due to different temperature and spectral dependence
## Overview – CIGS based tandem devices

<table>
<thead>
<tr>
<th>Top cell</th>
<th>Bottom cell</th>
<th>Tandem device</th>
</tr>
</thead>
<tbody>
<tr>
<td>Techn.</td>
<td>Efficiency [%]</td>
<td>Techn.</td>
</tr>
<tr>
<td>CdTe</td>
<td>13.8</td>
<td>CIS</td>
</tr>
<tr>
<td>AIGS</td>
<td>5.3</td>
<td>CIGS</td>
</tr>
<tr>
<td>CGS</td>
<td>4.3</td>
<td>CIGS</td>
</tr>
<tr>
<td>a-Si</td>
<td>3.1</td>
<td>CIS</td>
</tr>
</tbody>
</table>

* Tandem efficiency mainly limited by low performance and/or transmission of top cell

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* Efficiency gain compared to the sub cell with highest efficiency.
** Real efficiency gain unknown since unfiltered efficiency of bottom cell not measured/published

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* List not exhaustive
Theoretical efficiency limit for 2 junction tandem solar cells

Calculated maximum efficiency in the detailed balance limit for AM1.5G incident light. No optical losses included!

State-of-the-art perovskite solar cells

**Planar structure**

MAPbI₃

**Mesoporous structure**

\[(FAPbI₃)_{1-x}(MAPbBr₃)_x\]

\[Cs_x(MA_{0.17}FA_{0.83})_{100-x}Pb(I_{0.83}Br_{0.17})_3\]


J. Huang et al., Adv. Mater. 2016, DOI::10.1002/ADMA.201600969


\[\eta = 20.3\%\]

Jinsong Huang et al., Uni. Labraska Lincoln

M. Grätzel et al., EPFL: \(\eta = 21.1\%\)

S. Seok et al., KRICT: \(\eta = 22.1\%\)


http://www.nrel.gov/ncpv/images/efficiency_chart.jpg

Materials Science and Technology
Low-temperature NIR-transparent Planar Perovskite Solar Cells for Bifacial and Tandem Applications

Hybrid thermal evaporation/spin coating approach

- Combine the merits of both vapor and solution processes
  - **Vapor process**: homogeneous, compact and thickless controllable layer
  - **Solution process**: composition engineering,
- Explore solvent sensitive electron transporting layers and novel cell design

F. Fu et al., Nat. Commun. 2015, 10.1002/aenm.201301400
Suppressed J-V hysteresis with PCBM on glass substrate

AM1.5G, scan rate: 0.3 V/s, delay time: 10 ms

FB-SC: 1.2V to -0.1V
SC-FB: -0.1V to 1.2V

MPP tracker: perturb and observe

η = 15.6%

<table>
<thead>
<tr>
<th></th>
<th>$V_{oc}$ (V)</th>
<th>$J_{sc}$ (mA/cm²)</th>
<th>FF (%)</th>
<th>Eff. (%)</th>
<th>$\eta_{MPP}$ (%)</th>
<th>Area (cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FB-SC</td>
<td>1.075</td>
<td>19.1</td>
<td>73.6</td>
<td>15.1</td>
<td>15.6</td>
<td>0.15</td>
</tr>
<tr>
<td>SC-FB</td>
<td>1.076</td>
<td>19.1</td>
<td>74.7</td>
<td>15.3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

unpublished results
Semi-transparent planar perovskite solar cells

F. Fu et al., *Nat. Commun.* 2015, 10.1002/aenm.201301400
Bifacial perovskite solar cells

Mpp tracker: perturb and observation

Cell area: 0.517 cm²

F. Fu et al., Nat. Commun. 2015, 10.1002/aenm.201301400
Cl(G)S as bottom cell in tandem device

**Sample (best cell)** | CGI(±0.02) | GGI(±0.02) | Voc(mV) | Jsc(mA·cm⁻²) | FF(%) | η (%) |
---|---|---|---|---|---|---|
Reference | 0.79 | 0.34 | 718 | 34.7 | 76.1 | 19 |
14% CGI increase | 0.9 | 0.31 | 701 | 35.2 | 74.6 | 18.4 |
14% CGI increase (improved interface) | 0.89 | 0.34 | 718 | 35.9 | 76.8 | 19.9 |

- Adjustment of PDT and CBD processes required for changed CGI and GGI
- 1% gain in efficiency thanks to higher Jsc, FF
- **NIR response improved!**
- So far 0.7 mA/cm² gain

Towards CIS  
→ higher degree of freedom for buffer and window layer

E. Avancini et al., presented at E-MRS Spring Meeting 2016, May 2nd-6th, 2016, Lille, France
CI(G)S as bottom cell in tandem device - BSF

<table>
<thead>
<tr>
<th></th>
<th>[Ga]/([Ga]+[In])</th>
<th>$V_{OC}$ (mV)</th>
<th>$J_{SC}$ (mA/cm$^2$)</th>
<th>FF (%)</th>
<th>Eff (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.377</td>
<td>699</td>
<td>31.6</td>
<td>75.0</td>
<td>16.6</td>
</tr>
<tr>
<td>B</td>
<td>0.284</td>
<td>662</td>
<td>33.2</td>
<td>76.0</td>
<td>16.8</td>
</tr>
<tr>
<td>C</td>
<td>0.192</td>
<td>612</td>
<td>34.0</td>
<td>75.3</td>
<td>15.6</td>
</tr>
<tr>
<td>D</td>
<td>0.149</td>
<td>502</td>
<td>35.8</td>
<td>66.5</td>
<td>12.0</td>
</tr>
<tr>
<td>E</td>
<td>0.000</td>
<td>444</td>
<td>37.0</td>
<td>67.2</td>
<td>11.0</td>
</tr>
</tbody>
</table>

Decreasing GGI: $V_{OC}$ ↓, $J_{SC}$ ↑, FF ↓

T. Feurer et al., presented at EU-PVSEC 2015, Hamburg, Germany
CI(G)S as bottom cell in tandem device – front grading/In$_2$S$_3$

- $V_{OC}$ can be improved with front grading up to a certain steepness without mayor $J_{SC}$ losses
- Fill factor drops considerably for stronger front grading, diminishing the gains in $V_{OC}$
- In$_2$S$_3$ buffer allows a strong increase in $V_{OC}$, but the observed FF losses and light soaking behavior need to be addressed before it can be applied in devices.
Cl(G)S as bottom cell in tandem device – PDT/doping

Additional 20 minutes annealing @ ~350°C under Se atmosphere
CdS CBD, i-ZnO/AZO front-contact

<table>
<thead>
<tr>
<th></th>
<th>GGI</th>
<th>( V_{oc} ) (mV)</th>
<th>( J_{sc} ) (mA/cm²)</th>
<th>FF (%)</th>
<th>Eff (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CIS</td>
<td>0.00</td>
<td>444</td>
<td>37.0</td>
<td>67.2</td>
<td>11.0</td>
</tr>
<tr>
<td>CIS w/ annealing</td>
<td>0.00</td>
<td>491</td>
<td>39.1</td>
<td>72.6</td>
<td>13.9</td>
</tr>
</tbody>
</table>

- Post deposition treatment needs to be adjusted for Ga free CIS
- EQE shows weak near infrared response, indicating collection issues
- Combination of BSF, front grading and modified PDT required

T. Feurer et al., presented at E-MRS Spring Meeting 2016, May 2nd-6th, 2016, Lille, France
Perovskite-CIGS tandem device in 4-terminal configuration

20.5% Perovskite-CIGS in 4-terminal tandem configuration

F. Fu et al., Nat. Commun. 2015, 10.1002/aenm.201301400
### Perovskite-CIGS tandem solar cells: 4-terminal

<table>
<thead>
<tr>
<th>Sample</th>
<th>GGI [-]</th>
<th>$V_{OC}$ [mV]</th>
<th>$J_{SC}$ [mA/cm$^2$]</th>
<th>Fill factor [%]</th>
<th>Efficiency [%]</th>
<th>4t-Efficiency [%]</th>
<th>Efficiency gain [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perovskite top cell</td>
<td>-</td>
<td>1115</td>
<td>19.2</td>
<td>75.3</td>
<td>16.1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CIGS Masked</td>
<td>0.35</td>
<td>723</td>
<td>35.6</td>
<td>76.2</td>
<td>19.6</td>
<td>22.1</td>
<td>2.5</td>
</tr>
<tr>
<td>CIGS Filtered</td>
<td>0.35</td>
<td>665</td>
<td>12.1</td>
<td>74.2</td>
<td>6</td>
<td>22.1</td>
<td>2.9</td>
</tr>
<tr>
<td>CIGS Masked</td>
<td>0.37</td>
<td>696</td>
<td>35.6</td>
<td>77.3</td>
<td>19.2</td>
<td>22.1</td>
<td>2.9</td>
</tr>
<tr>
<td>CIGS Filtered</td>
<td>0.37</td>
<td>669</td>
<td>12.1</td>
<td>73.6</td>
<td>6</td>
<td>21.9</td>
<td>2.8</td>
</tr>
<tr>
<td>CIS masked</td>
<td>-</td>
<td>453</td>
<td>39.2</td>
<td>73.1</td>
<td>13</td>
<td>20.9</td>
<td>4.8 (7.9)</td>
</tr>
<tr>
<td>CIS filtered</td>
<td>-</td>
<td>428</td>
<td>15.3</td>
<td>73.1</td>
<td>4.8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Unpublished results

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Perovskite based tandem solar cells – efficiency gain

\[ \Delta \eta = 2.9\% \]

\[ \Delta \eta = 2\% \]

Conclusion and Outlook

- Perovskite and CIGS devices are suitable partners for high efficiency tandem devices

- Clear efficiency gain in tandem devices compared to sub cells already achieved

- Low-temperature grown all-thin-film PV device in tandem configuration with efficiency >22% → suitable for flexible substrate

sub-cell efficiency – band gap of top and bottom cell – transmission through top cell – recombination layer – NIR response in bottom cell – stability of top cell …
Outlook: flexible perovskite-CIGS tandem devices

Flexible thin-film tandem device to overcome Shockley-Queisser single junction limit.

Challenges?

• Low-temperature flexible top cell
• Highly efficient NIR-transparent flexible perovskite solar cell
Outlook: flexible perovskite-CIGS tandem devices

<table>
<thead>
<tr>
<th></th>
<th>( V_{OC} ) (V)</th>
<th>( J_{SC} ) (mA/cm(^2))</th>
<th>FF (%)</th>
<th>( \eta ) (%)</th>
<th>( \eta_{MPP} ) (%)</th>
<th>Cell area (cm(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>CIGS</td>
<td>0.66</td>
<td>34.7</td>
<td>77.7</td>
<td>17.8</td>
<td>17.8</td>
<td>0.213</td>
</tr>
<tr>
<td>CIGS bottom cell</td>
<td>0.63</td>
<td>12.6</td>
<td>77.1</td>
<td>6.1</td>
<td>6.1</td>
<td>0.213</td>
</tr>
<tr>
<td>Perovskite top cell</td>
<td>1.07</td>
<td>14.7</td>
<td>62.2</td>
<td>9.8</td>
<td>9.9</td>
<td>0.28</td>
</tr>
</tbody>
</table>

**Tandem: 16%; \( \Delta \eta = -1.8\%)**
Acknowledgements
The Competence Center for Energy and Mobility in ETH Domain and Swiss Federal Office of Energy: CONNECT-PV
The Swiss National Science Foundation NRP70: PV-2050
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NanoTera: Synergy-Gateway
Flisom AG

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