Parasitic absorption and light management in PK/Si tandem cells

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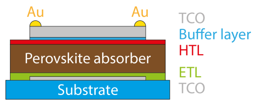
Introduction & Motivation

- Tandem solar cells made from a crystalline silicon (c-Si) bottom cell and a wide-band-gap top cell improve the utilization of the incident light's spectrum which reduces thermalization losses
- Monolithic (2TT) and four-terminal (4TT) c-Si/perovskite tandem cells suffer from specific sources of parasitic absorption arising from transparent electrodes and charge transport layers
- Addressing these parasitic losses and implementing proper light management for both architectures is crucial to improve current generation and overall tandem performance.

Top cell and tandem fabrication

Top cell fabrication:

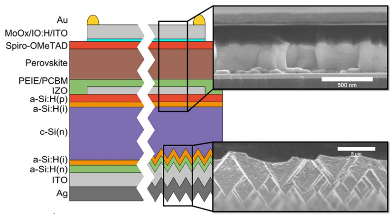
- Spin-coat PEIE onto TCO/glass substrate to functionalize oxide surface (TCO: FTO, ITO, …)
- Spin-coat electron transport layer (ETL; here: PCBM) onto functionalized substrate
- Deposit PbI_2 in vacuum system
- Spin-coat MAI, annealing to form PK absorber
- Spin-coat hole transport layer (HTL; here: spiro-OMeTaD)
- Thermal evaporation of buffer layer (MoO_x or WO_x)
- TCO sputtering

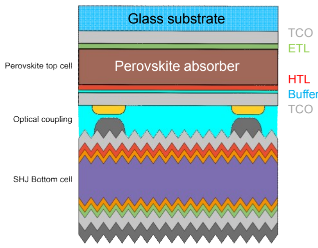


Result: NIR-transparent top cell with 16 % steady efficiency and negligible hysteresis

Monolithic tandems (2TT):
Processing PK top cell directly on SHJ cell, connecting cells by recombination layer. Process temperatures strictly below 200 °C.

Four-terminal tandems (4TT):
Mechanically stacking PK cell onto c-Si cell: independent processing of sub-cells, no constraints for PK orientation and polarity





J. Werner *et al.*, J. Phys. Chem. Lett. **7**, 161 (2016)
J. Werner *et al.*, ACS Energy Lett. **1**, 474 (2016)

Perovskite/c-Si monolithic tandem device (2TT)

- The introduction of a texture at the rear-side of the bottom cell helps to reduce reflection losses at wavelengths >1000 nm
- 2TT efficiency (state-of-the-art): **20.5 %** on 1.43 cm^2, after > 5 min maximum power point tracking.

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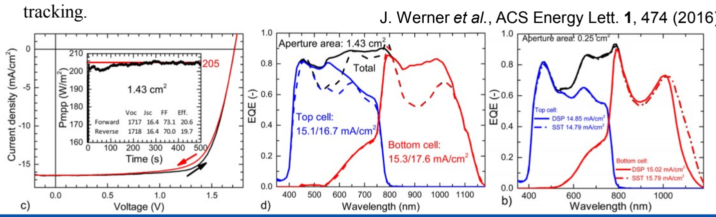

Direct comparison between tandem architectures

- **Wavelengths < 600 nm:**
  - 4TT performs better – free choice of illumination direction in the top cell
- **Wavelengths > 900 nm:**
  - 2TT performs better – less and thinner TCO in device, thus lower free-carrier absorption
- Total current:
  2TT: 34.3 mA/cm^2; 4TT: 35.9 mA/cm^2;
  SHJ: 39.6 mA/cm^2

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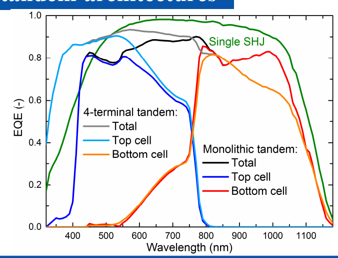


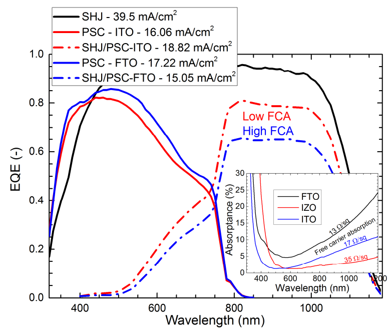
Parasitic absorption in tandem cells

Monolithic tandems (2TT):

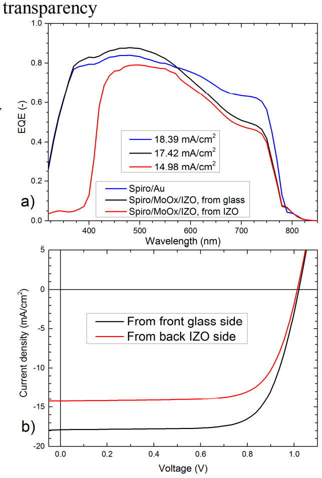
- The highly doped hole transport layer, Spiro-OMeTAD, parasitically absorbs over the entire spectral range, in particular for wavelengths below 400 nm
- J_{sc} loss of about 2-3 mA/cm^2 when cell illuminated from spiro side.
- Transparent electrode: top TCO with wide-range transparency

Four-terminal tandems (4TT):

- Parasitic absorption in TCO electrodes: strong free-carrier absorptions in FTO front electrode
- Find electrodes and buffer layer which are highly transparent and have low sheet resistances



Effect of TCO choice on EQE of a 4TT



Effect of top cell illumination direction on EQE (top) and IV curves (bottom)

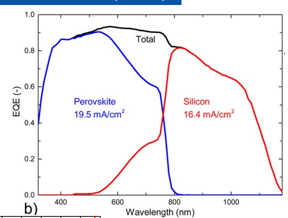
Light management and reduction of parasitic absorptions:

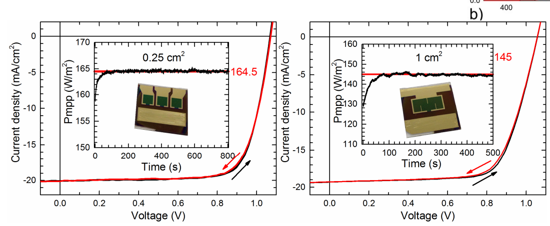
- Applying micro-textured antireflective foils: lower reflection losses and increased light trapping for higher current generation
- Changing buffer layer material from MoO_x to WO_x and treating with CO_2 plasma decreases parasitic absorption by 2-3 $\%_{abs}$
- **2TT:** Replace spiro-OMeTAD with more transparent HTL (e. g., high-E_g inorganic material)
- **4TT:** Replacing FTO by ITO causes a current increase of 3-4 mA/cm^2 in the bottom cell

J. Werner *et al.*, Sol. Energ. Mat. Sol. Cells **141**, 407 (2015)
J. Werner *et al.*, ACS Appl. Mater. Interfaces **8**, 17260 (2016)

Perovskite/c-Si 4-terminal tandem device (4TT)

- ➢ NIR-transparent perovskite top cell :
  16.4 % (0.25 cm^2), **14.5 %** (1 cm^2)
- ➢ Silicon bottom cell, (4 cm^2):
  22.1 % (non-filtered), **8.8 %** (filtered)
- ➢ 4TT-measurement:
  25.2 % (0.25 cm^2), **23 %** (1 cm^2)





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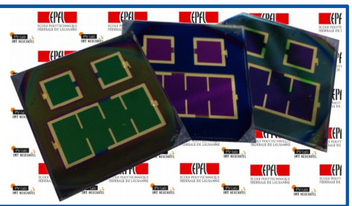
Conclusions

- ➢ Using more transparent TCOs and substrates, as well as minimizing the reflection at the air interfaces, allowed enhancement of tandem performance
- ➢ Choosing a better suited buffer layer material and a suitable post-treatment further decreased parasitic absorption
- ➢ The elimination of parasitic absorption in the hole transport layer (spiro-OMeTAD) is crucial to reach higher efficiencies in monolithic tandems
- ➢ World-record performances on both 4-terminal and monolithic tandems:
  - ➢ 4-terminal tandem measurements with efficiency of 25.2 %, after mpp tracking of 500 s
  - ➢ Monolithic tandem cells with up to 21.2 and 20.5 % efficiencies on 0.17 and 1.43 cm^2 aperture area, respectively.



See Talk B2.14 (Sep. 28, 18:15)

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