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# Perovskite/c-Si tandem solar cells: 4-terminal and monolithic integration

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## Introduction & Motivation

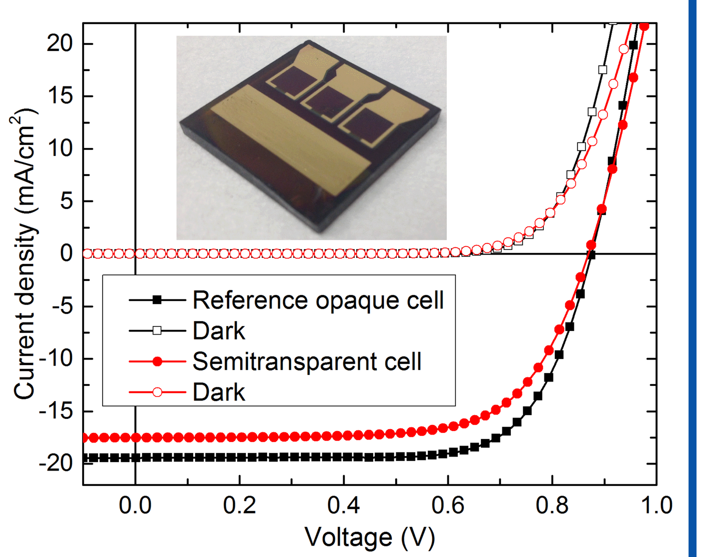
- The photovoltaics market is dominated by wafer-based crystalline silicon solar cells. With a record efficiency of 25.6%, close to their theoretical maximum efficiency of 29.4%.
- Perovskite-based solar cells have recently made tremendous progress and currently reach efficiencies of up to 22.1%
- Perovskite/crystalline Si cells optimally use the solar spectrum: The perovskite cell absorbs the visible light, the crystalline Si cell the near-infrared light
- Numerical simulations have predicted perovskite/ crystalline Si tandem efficiencies of > 30%
- The perovskite top cell needs to be semitransparent and have high transmittance in the near-infrared → Need to replace opaque metal contact with transparent electrode
- Two tandem device architectures: four-terminal mechanically stacked or two-terminal monolithic tandem

## Transparent Rear Electrode for Perovskite Solar Cells

**Requirement**: high near-infrared transparency for maximal light transmission to bottom cell

**Sputtered amorphous TCO:** IZO, high conductivity, high transparency, high mobility with low carrier density, reproducible and industrially compatible process, low-temperature deposition, no post-deposition treatment needed

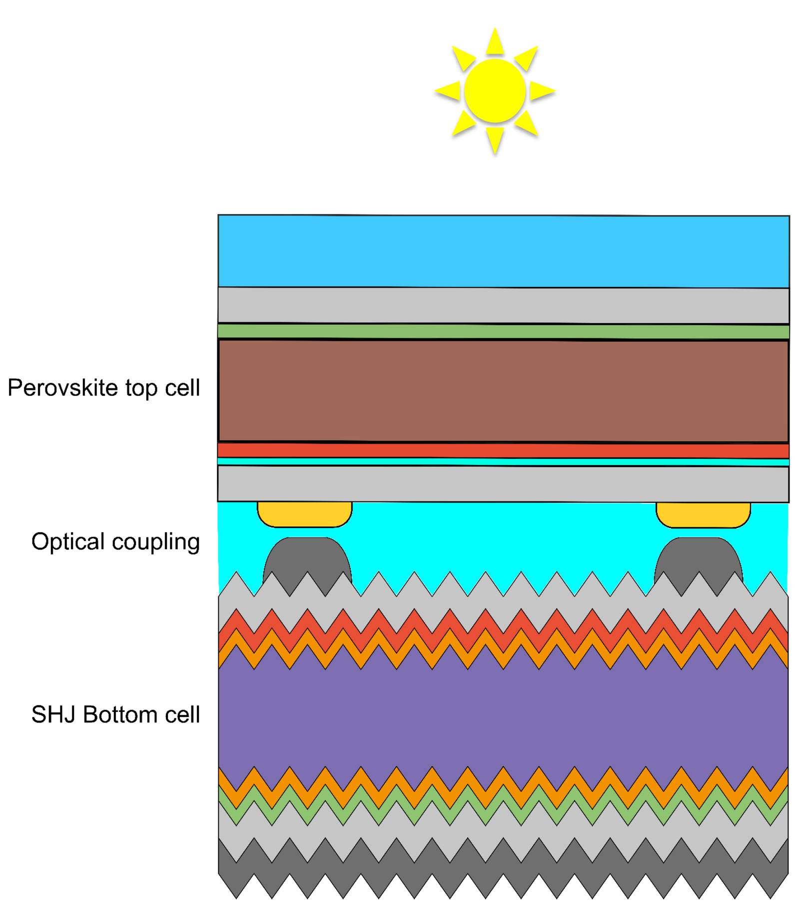
**Rear electrode:** sputter damage avoided with introduction of thin molybdenum oxide layer, no FF and $V_{oc}$ losses, $J_{sc}$ reduction due to lack of rear reflector
Semitransparent cell performance comparable to opaque cells

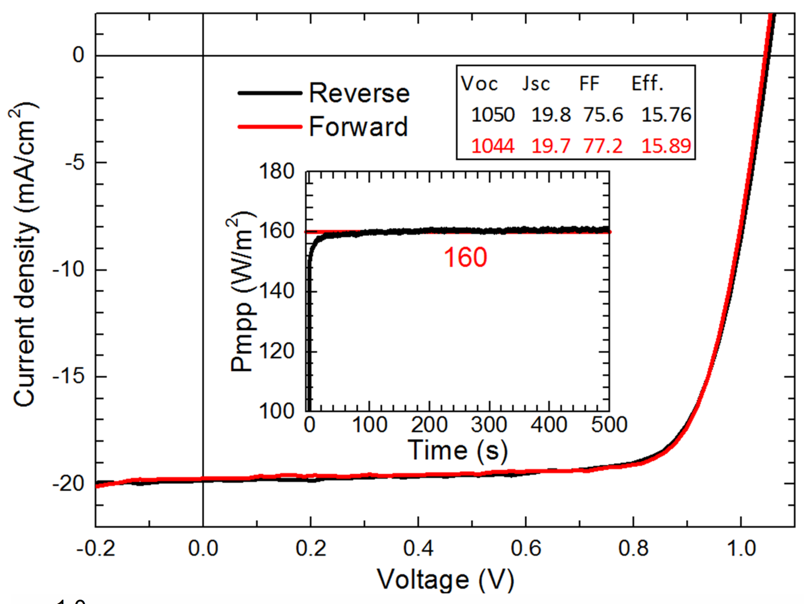


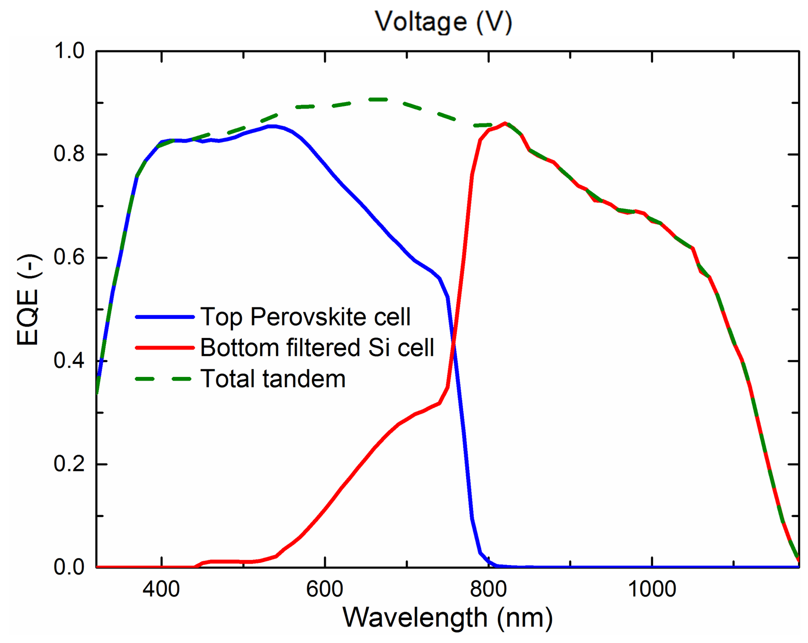

J. Werner *et al.*, SolMat, **141** (2015) 407-413

## Perovskite/c-Si 4-terminal tandem device

- The perovskite cell is mechanically stacked on a crystalline Si cell, allowing for independent processing of both sub-cells.
- No constraints for the orientation/polarity of the perovskite cell.
- 3 highly transparent electrodes with low sheet resistance are required.
- The photocurrent in the silicon bottom cell is limited by parasitic absorption in the perovskite top cell
- 4-terminal measurements:
  - Semitransparent perovskite top cell (0.25 cm²): **16% mpp tracker**
  - Silicon bottom cell, non-filtered, (4 cm²): **21.7%**
  - Silicon bottom cell, filtered: **9%**
  - Total tandem: **25%mpp tracker**



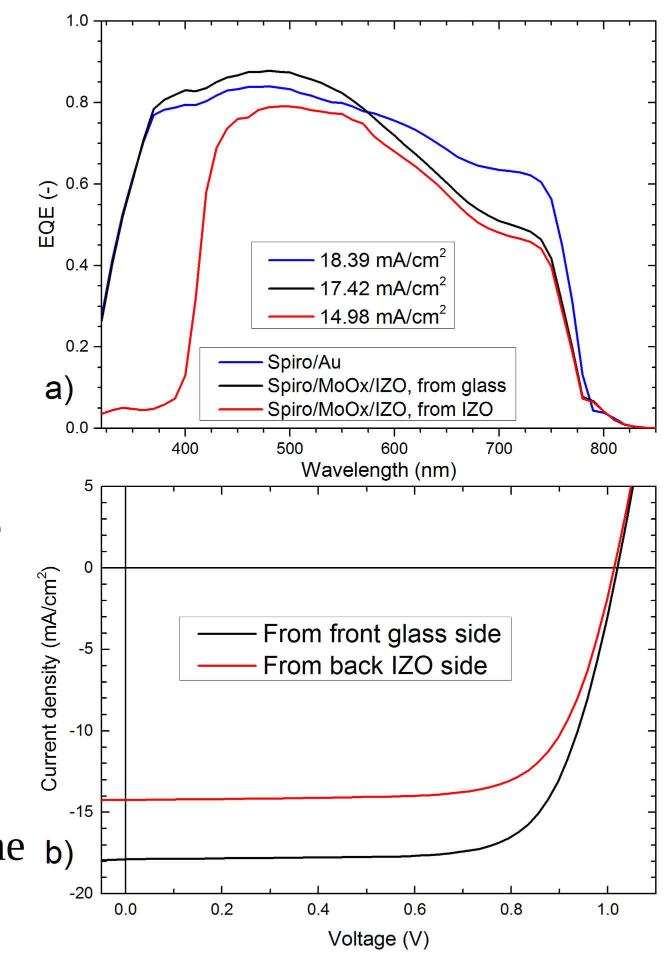



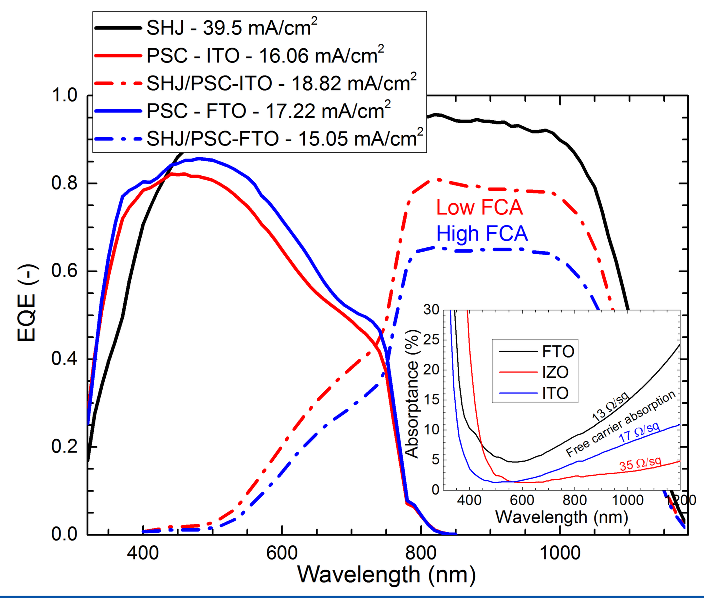



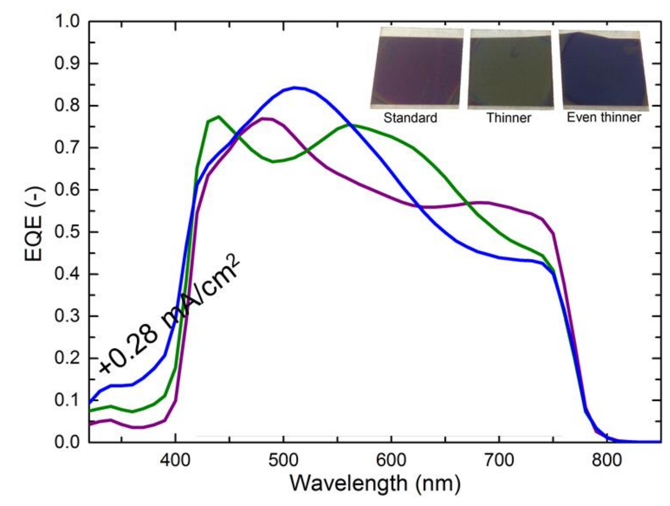

J. Werner *et al.*, Presented at MRS Spring 2016, Phoenix

## Parasitic absorptions

- Reducing the parasitic absorption in the perovskite top cell is the key for high performance in both 4-terminal and monolithic tandem.
- In the case of 4-terminal tandem, the standard front electrode used in perovskite cell (FTO) need to be replaced by a TCO with lower free carrier absorption, e.g. ITO.
  Replacing FTO by ITO produces a current increase in the bottom cell of 3-4 mA/cm².
- In the case of monolithic tandem, the highly doped hole transport layer, Spiro-OMeTAD, parasitically absorbs over the entire spectral range, and particularly for wavelengths below 400nm.
  → Jsc loss of about 2-3 mA/cm² when illuminate from spiro side.
- Reducing the thickness of spiro can help to recover some current <400nm. But changes interference pattern.

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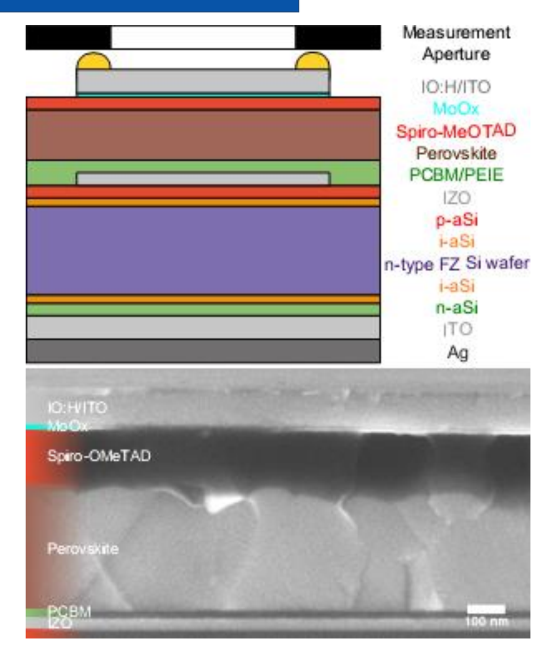
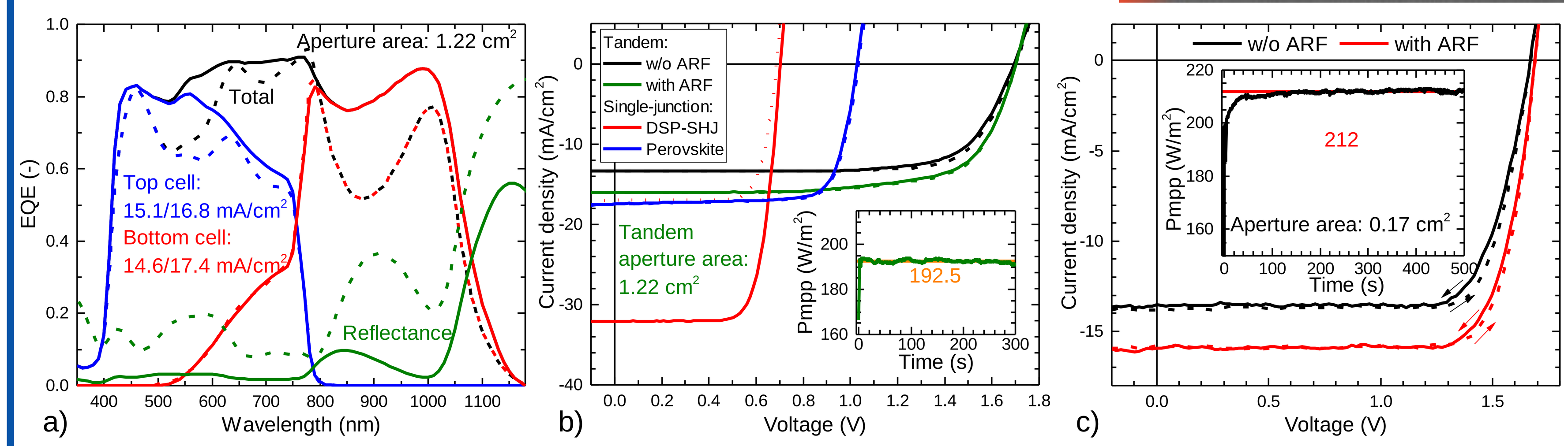
## Perovskite/c-Si monolithic tandem device

- The perovskite cell is processed directly on top of the silicon bottom cell, connected by an intermediate recombination layer.
- low-temperature (<200°C) processed perovskite top cell on silicon heterojunction bottom cell
- Interferences play a large role on current matching

- Monolithic tandem efficiency (state-of-the-art): 21.2% on 0.17cm² and 19.2% on 1.22cm², after >5min maximum power point tracking.




J. Werner *et al.*, JPCL 2016, **7**, 161-166

## Conclusions

- Sputtered transparent conductive oxide rear electrodes with metal oxide buffer layers enable semitransparent cells showing comparable performance as opaque references
- Using more transparent TCOs and substrates, as well as minimizing the reflection at the air interfaces allows to further enhance tandem performance
- The elimination of parasitic absorption (e.g. in FTO, spiro-OMeTAD) is crucial to reach higher tandem cell efficiencies
- World record performances on both 4-terminal and monolithic tandems:
  - 4-terminal tandem measurements with efficiency of up to 25%, after mpp tracking of 500s
  - Monolithic tandem cells with up to 21.2 and 19.2% efficiency, respectively on 0.17 and 1.22cm² aperture area.