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Near-infrared transparent perovskite solar cells for Si-based tandem applications

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Motivation

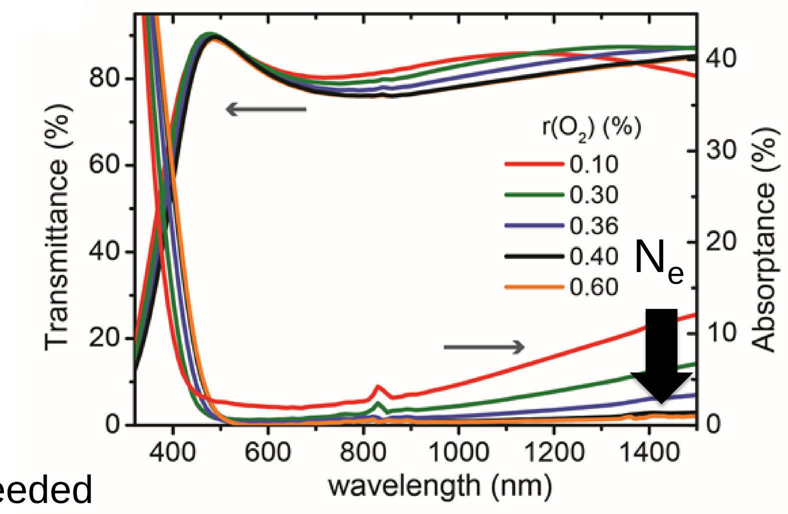
- The photovoltaics market is dominated by wafer-based crystalline silicon solar cells. With a record efficiency of 25.6%, close to their practical performance limit of 26%.
- Perovskite-based solar cells have recently made tremendous progress and currently reach efficiencies of up to 20.1%
- Perovskite/crystalline 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

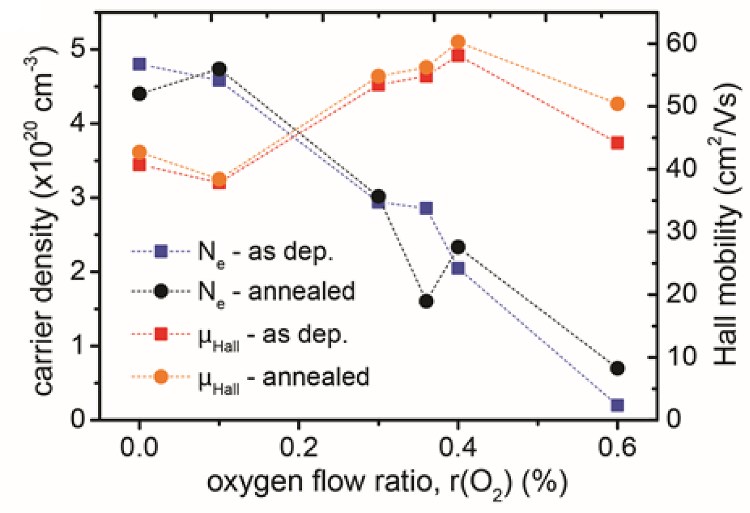
➢ Need to replace opaque metal contact with transparent electrode

Transparent Conductive Oxides

Advantages of sputtered amorphous TCOs:

✓ High conductivity
✓ High broadband transparency
✓ High mobility (>50cm^2/Vs) and low carrier density: low NIR parasitic absorption
✓ Reproducible and industrially compatible process
✓ Low-temperature deposition
✓ No post-deposition treatment needed

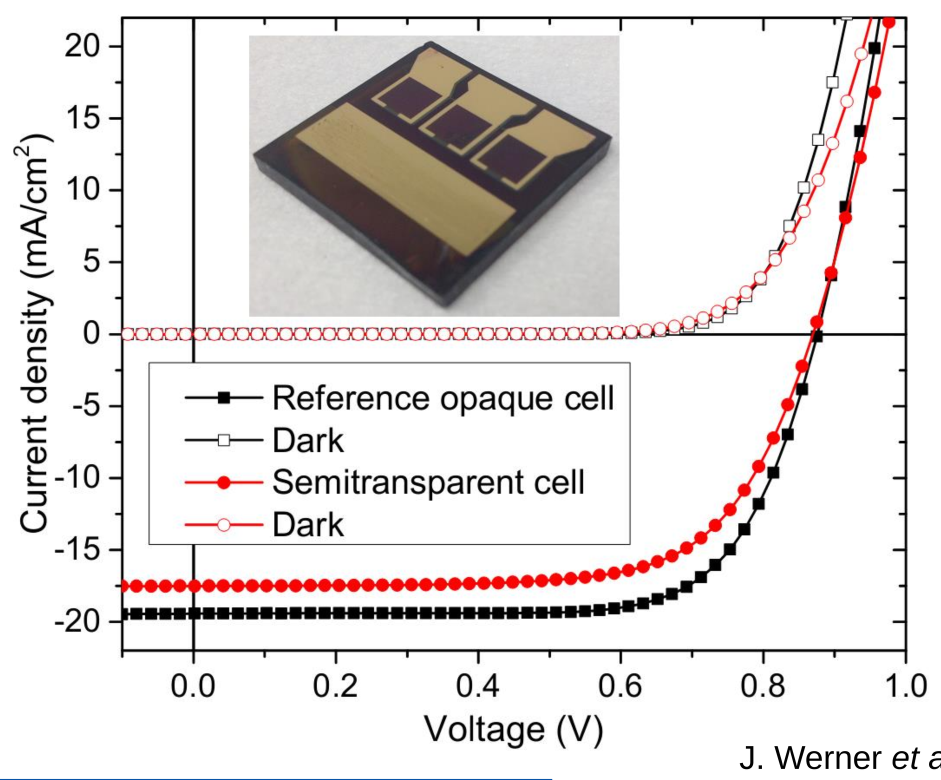


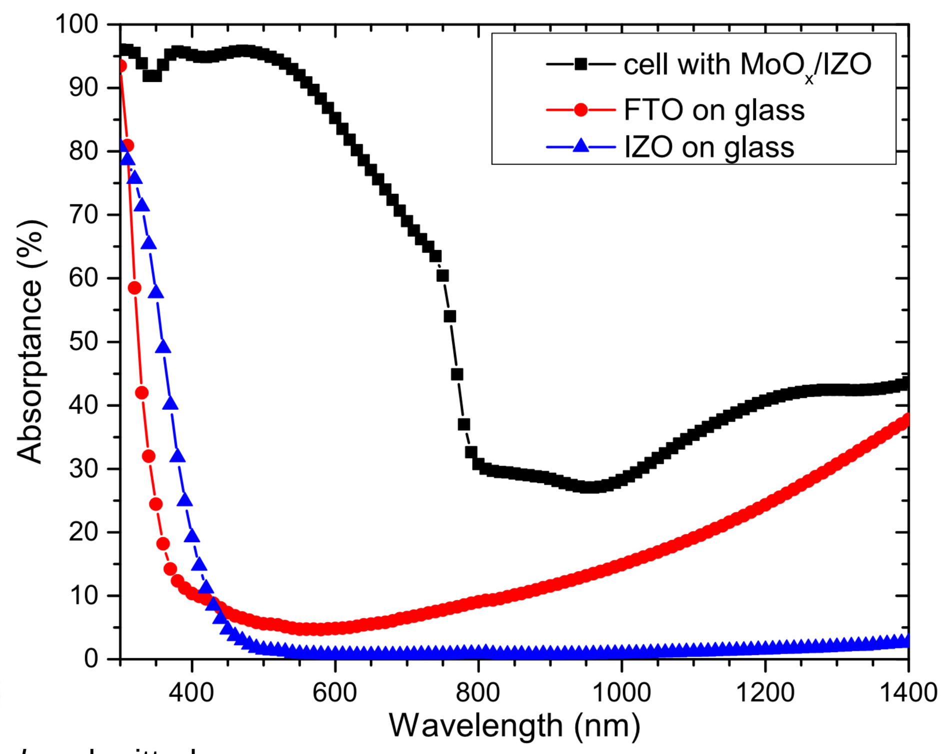


M. Morales-Masis et al. Submitted IEEE JPV

Transparent rear electrode

- Requirements for the transparent rear electrode:
  - ➢ High near-infrared transparency for maximal light transmission to the silicon bottom cell
  - ➢ Low sheet resistance for efficient carrier extraction
  - ➢ Smooth deposition, to avoid damaging underlying sensitive layers
- Sputtered transparent conductive oxides with metal oxide buffer layers (to avoid sputter damage) fulfill these requirements
- Molybdenum oxide/indium zinc oxide rear electrodes enable semitransparent cells with efficiencies of up to 10.3%, compared to an opaque reference cell at 12.5%. Layer stack: FTO/TiO_2/TiO_2:$CH_3NH_3PbI_3$/spiro-OMeTAD/MoO_x/IZO
- No FF and Voc losses: sputter damage could be completely avoided
- Jsc losses, explained by lack of rear reflector
- Limitations of the semitransparent cell: FTO, spiro-OMeTAD





J. Werner *et al.*, submitted

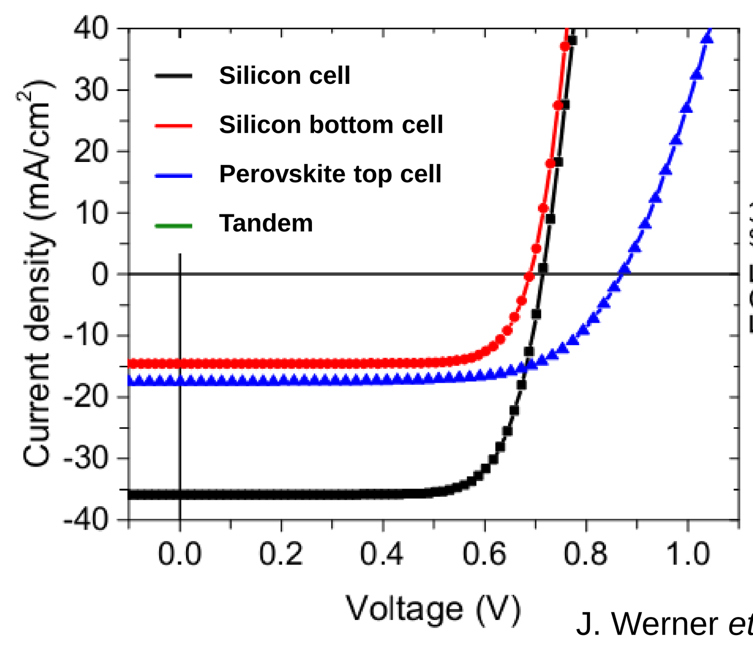
4-terminal tandem devices

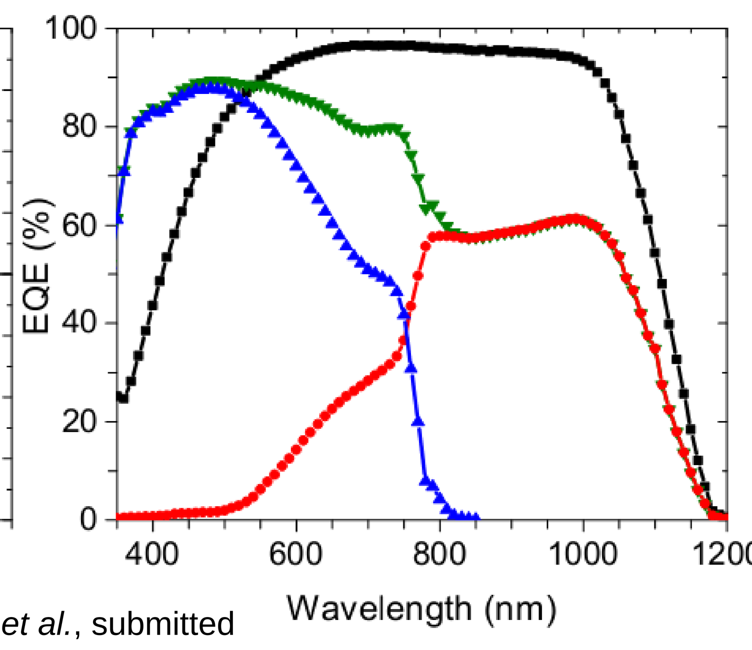
4-terminal tandem

- The perovskite cell is mechanically stacked on a crystalline Si cell, allowing for independent processing of both sub-cells
- 2-3 highly transparent electrodes with low sheet resistances are required
- No constraints for the orientation/polarity of the perovskite cell

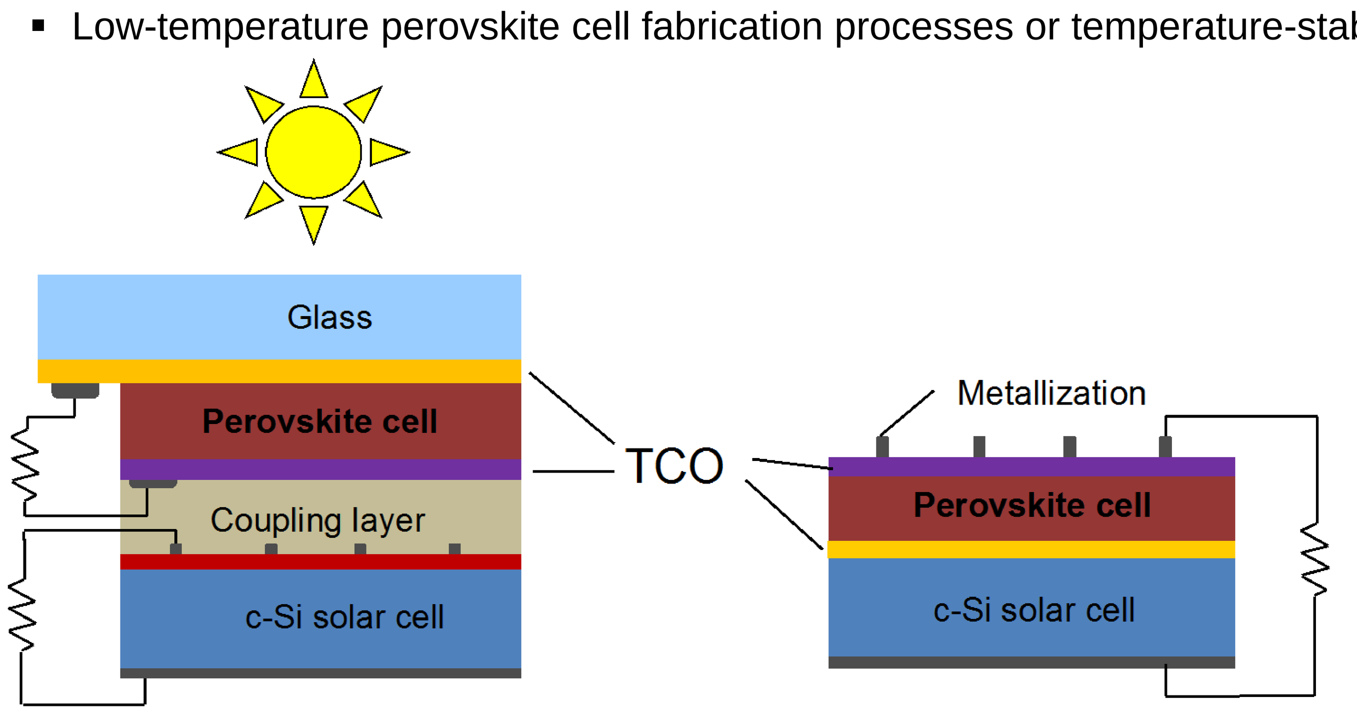
Monolithic tandem

- The perovskite cell is processed on the Si cell
- Only 1 highly transparent electrode with a low sheet resistance is required
- Low-temperature perovskite cell fabrication processes or temperature-stable Si cell are required





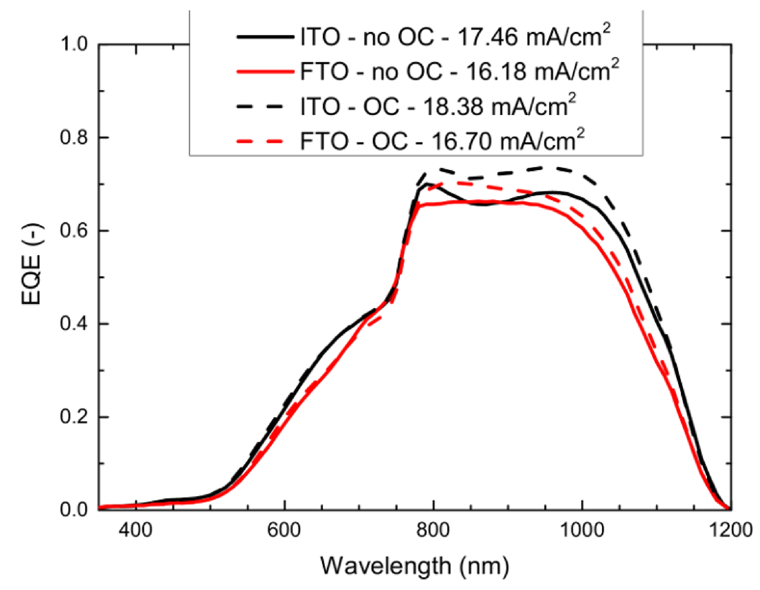
J. Werner *et al.*, submitted



4-terminal tandem (mechanically stacked)

Monolithic (2-terminal) tandem

- Amorphous Si/crystalline Si heterojunction (a-Si/c-Si HJ) cells are ideal bottom cells due to their high quantum efficiency in the near-infrared
- 4-terminal efficiencies of up to 18.2% are reached with a FTO/TiO_2/TiO_2:$CH_3NH_3PbI_3$/spiro-OMeTAD/MoO_x/IZO top cell and an a-Si/c-Si HJ bottom cell
- The photocurrent in the silicon bottom cell is still limited by parasitic absorption, mainly by the FTO front electrode of the perovskite cell
- Overall performance can be enhanced by replacing FTO by ITO, more transparent in the NIR, and by using a proper optical coupling system between the two sub-cells.



Conclusions

❖ Sputtered transparent conductive oxide rear electrodes with metal oxide buffer layers enable semitransparent cells with efficiencies of up to 10.3%

❖ 4-terminal tandem devices with efficiencies of up to 18.2% were first fabricated.

❖ Using more transparent TCOs and substrates, as well as minimizing the reflection at the air interfaces allows to further enhance the overall 4-terminal tandem efficiency

❖ The elimination of parasitic absorption (e.g. in FTO, spiro-OMeTAD) is crucial to reach higher tandem cell efficiencies

Litterature

➢ J. Werner *et al.*, *Sputtered rear electrode with broadband transparency for perovskite solar cells,* SUBMITTED

➢ P. Löper *et al.*, *Organic–inorganic halide perovskite/crystalline silicon four-terminal tandem solar cells*, Phys. Chem. Chem. Phys. 17, 1619 (2015)

➢ M. Filipič *et al.*, *$CH_3NH_3PbI_3$ perovskite / silicon tandem solar cells: characterization based optical simulations*, Opt. Express (2015)

➢ P. Löper *et al.*, *Complex refractive index spectra of CH3NH3PbI3 perovskite thin films determined by spectroscopic ellipsometry and spectrophotometry,* J. Phys. Chem. Lett. 6 (1), 2015

➢ P. Löper *et al.*, *Organic–Inorganic Halide Perovskites: Perspectives for Silicon-Based Tandem Solar Cells,* IEEE J. Photovolt. 4, 1545 (2014)