FRAUNHOFER - Solar Cell Manufacturing & Characterization

Dr. Martin Schubert

Freiburg, 30.11.2022
www.ise.fraunhofer.de

Fraunhofer Infrastructure in for VIPERLAB

Characterization @ ISE (Freiburg)

- **IV analyses** with optimizes sun simulators
- **External Quantum Efficiency** (EQE) Setups, optimized for tandem solar cells
- Camera-based **luminescence imaging** for tandems (up to 210mmx210mm) @450nm and 808nm
- Camera-based **lock-in thermography** with illumination at different wavelengths (470 nm, 655 nm, 950 nm) or external voltage
- **Microscopic photoluminescence spectroscopy** via confocal microscopy with various excitation wavelengths (532 nm, 640 nm, 905 nm) and high spatial resolution (approx. 1µm).

Nano-Analytics @ CSP (Halle)

- **Fabrication of specific test structures** and devices (laser processing, soldering, lamination/encapsulation) Defect localization at module level (EL, LIT, EQE, PL, Raman, Microscopy, X-ray tomography)
- **Target preparation** (metallography, fs/ps/ns-laser preparation, FIB techniques)
- LED **SoSim** & High Resolution **Hyper Spectral Imaging**
- **Micro analysis** (SEM/EDS/EBSD/EBIC, µLBIC, electrical and optical micro characterization, ICPMS, LIBS)
- High resolution **nano-analytics** (TEM, TOFSIMS, XPS/UPS, AES, ISS)

PeroLab @ ISE (Freiburg)

- High efficiency silicon **bottom solar cells**
- **Vacuum deposition technologies**: TCO and selective contact sputtering, evaporation (metal, organics, metal oxides), ALD (SnOx, AlOx, ZTO ...).
- **Vacuum deposition** of perovskite absorbers, also **hybrid processing**
- **Wet chemical processing** of perovskite solar cells
- Perovskite silicon tandem solar **cell base lines**
- Range of **metallisation** concepts
- Electrically conductive **adhesive bonding** for low-T interconnection for later module incorporation
- Processing is possible throughout for sample sizes of up to 156x156 mm^2.

Fraunhofer ISE

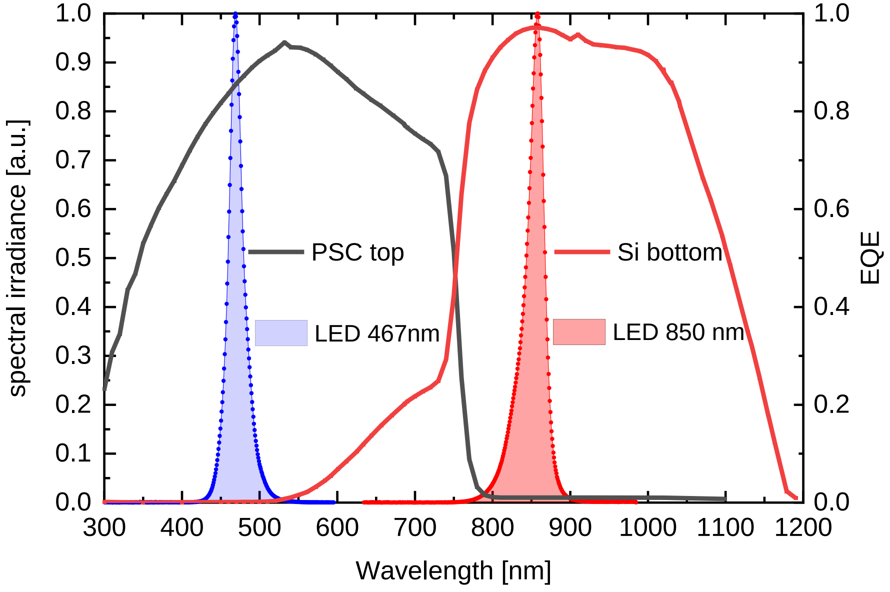
Characterization of Pero(tandem) solar cells

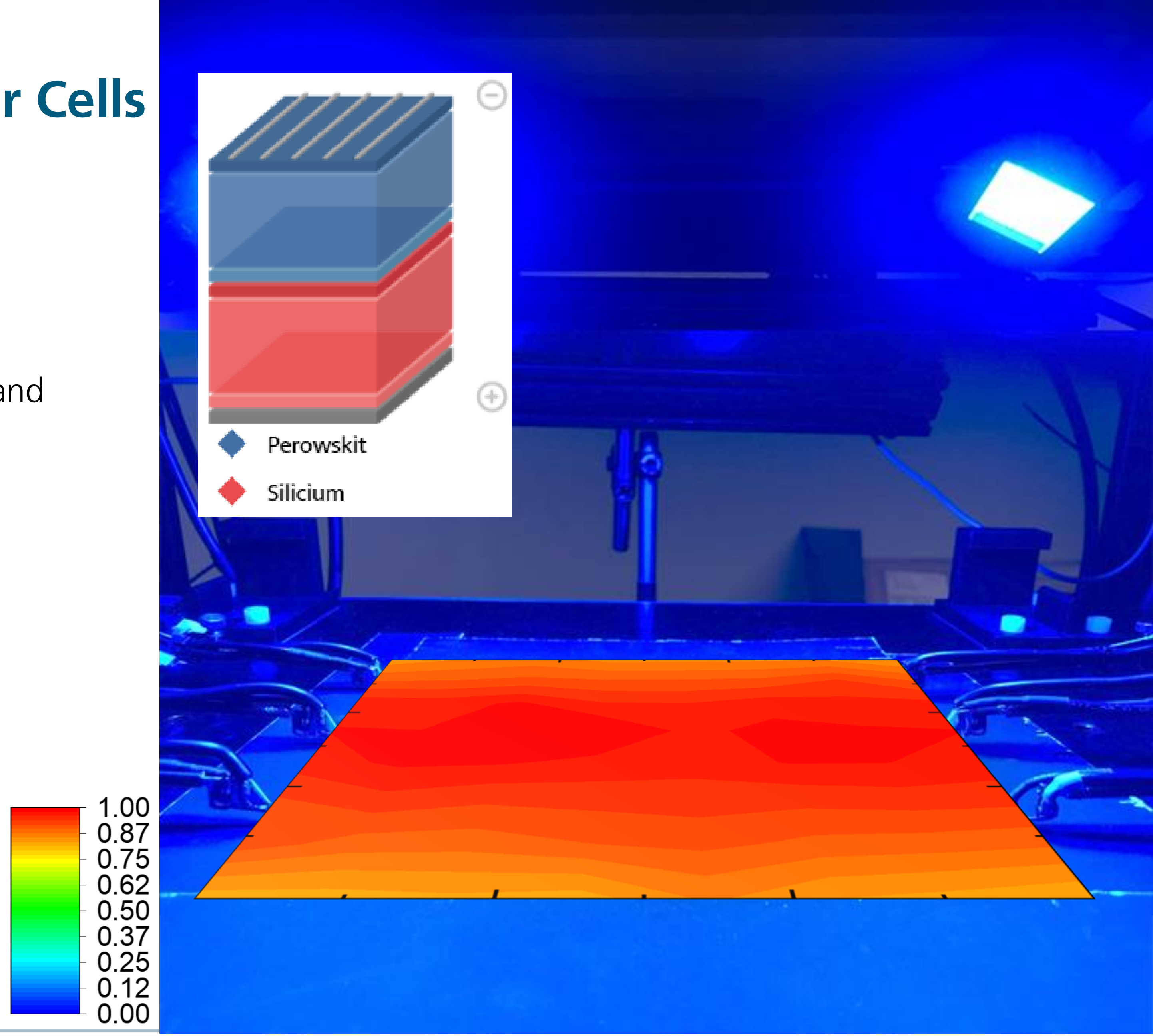
Analysis of Perovskite Silicon Solar Cells

Precise Cell Measurements

Global cell parameters

- External quantum efficiency with homogeneous bias and tunable laser illumination





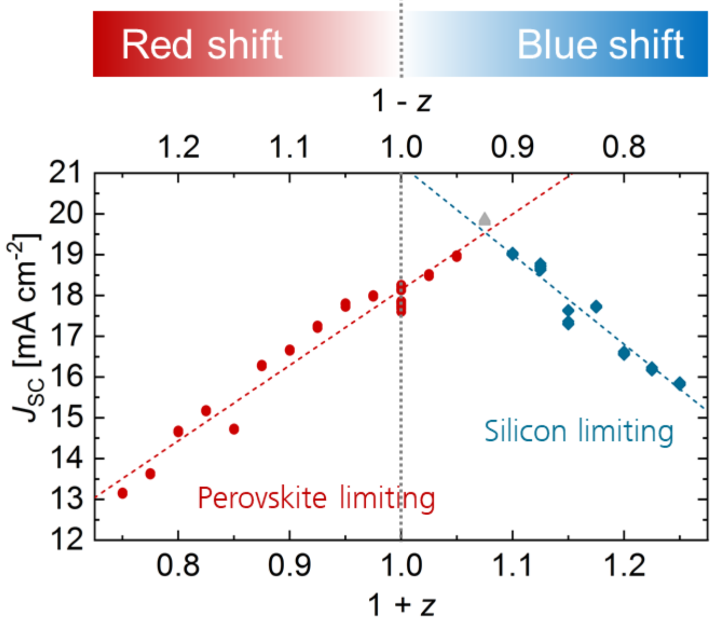
Analysis of Perovskite Silicon Solar Cells

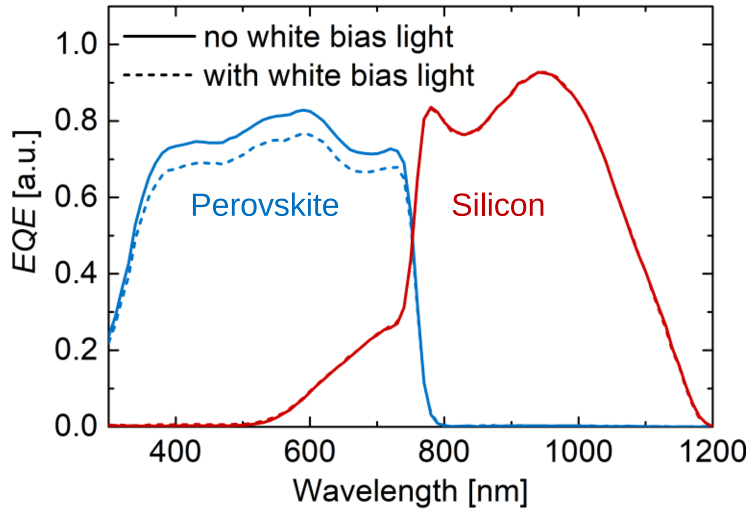
Precise Cell Measurements

Global cell parameters

- External quantum efficiency with homogeneous bias and tunable laser illumination
- Spectral metric analyses

→ Spectral metric analysis needed for correct determination of current matching point





Integrated current: 18.5 mA cm^{-2}

Integrated current: 17.9 mA cm^{-2}

→ Silicon bottom cell seems to limit the cell

Integrated current: 17.2 mA cm^{-2}

Integrated current: 17.9 mA cm^{-2}

→ Perovskite top cell seems to limit the cell

Bett, A. et al. solar-rrl, accepted

Analysis of Perovskite Silicon Solar Cells

Precise Cell Measurements

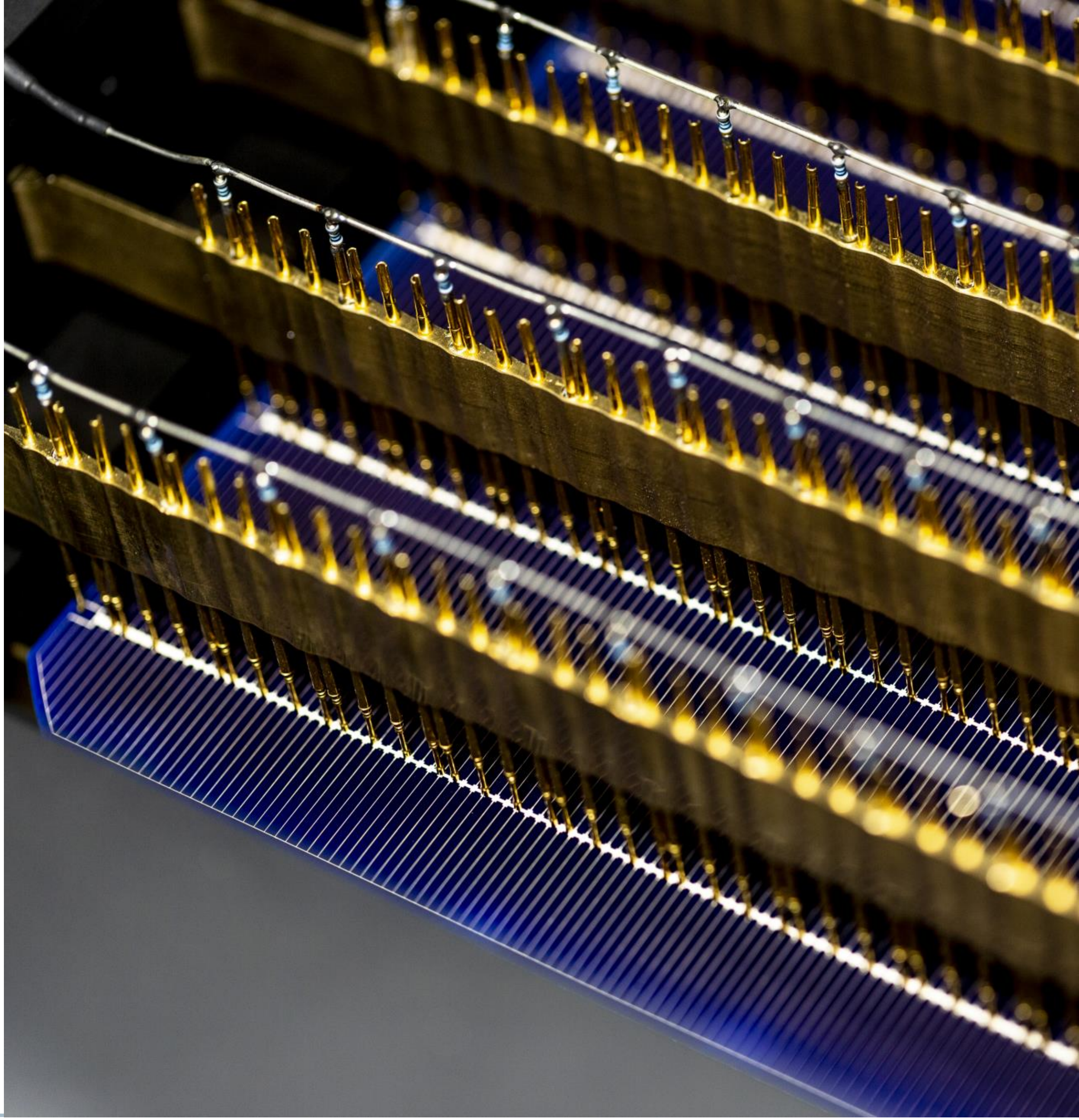
Calibration of Pero-Si tandem solar cells (beyond Viperlab Infrastructure)

- Regular cell calibrations at Fraunhofer ISE CalLab Cells
- Calibration of small but also large cells (>16x16cm²)

https://www.ise.fraunhofer.de/en/rd-infrastructure/accredited-labs/callab/callab-pv-cells.html

cells@callab.de

CalLab
PV Cells



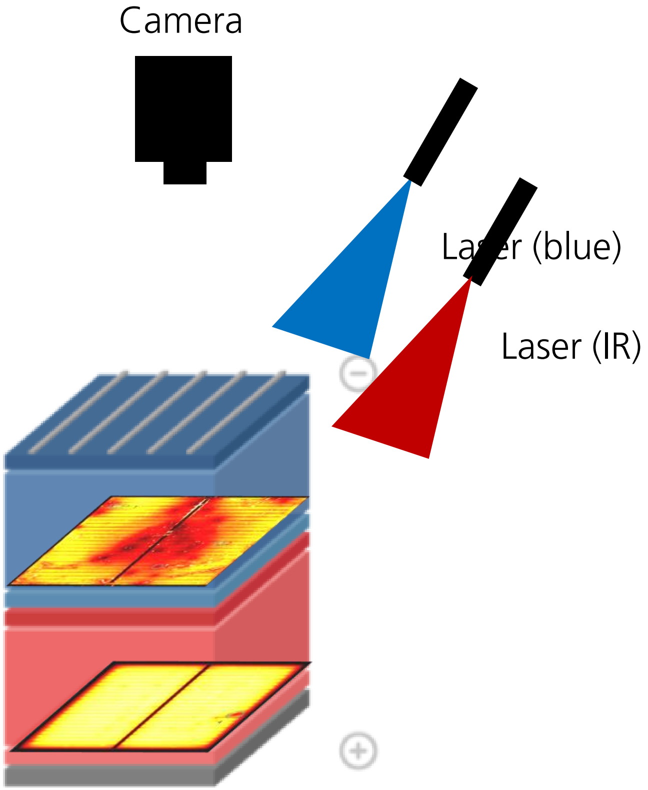
Fraunhofer ISE

Analysis of Perovskite Silicon Solar Cells

Analysis of Sub Cell Inhomogeneities

PL Imaging for tandem solar cells

- Own development for tandem-optimized setup
- Selective sub-cell excitation and detection
- Camera based measurements to analyse
  - Layer homogeneities
  - Material quality
  - Local voltage
  - Resistance distribution

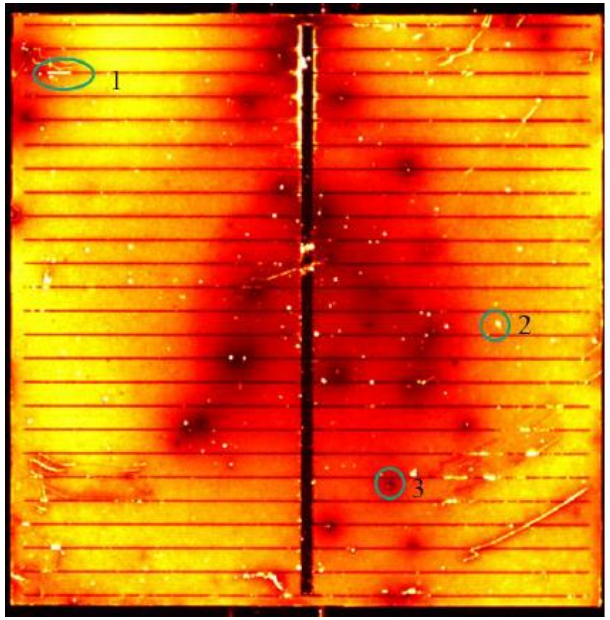


Analysis of Perovskite Silicon Solar Cells

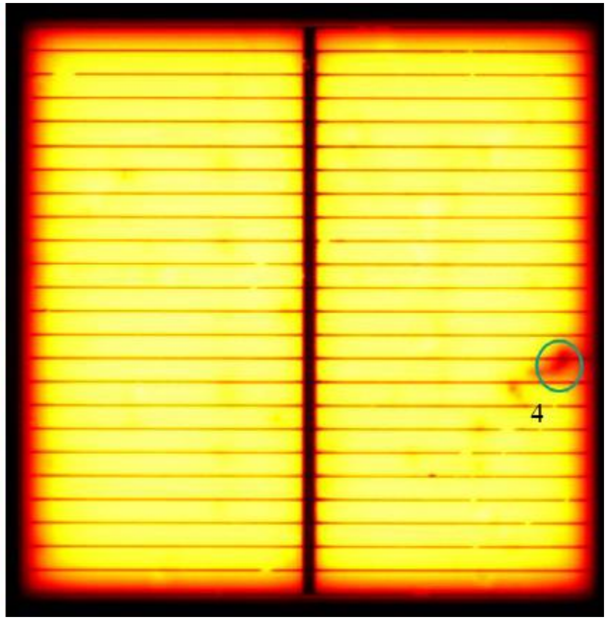
Analysis of Sub Cell Losses

PL Imaging for tandem solar cells

- Own development for tandem-optimized setup
- Selective sub-cell excitation and detection
- Camera based measurements to analyse
  - Layer homogeneities
  - Material quality
  - Local voltage
  - Resistive losses



PLI Perovskite sub cell



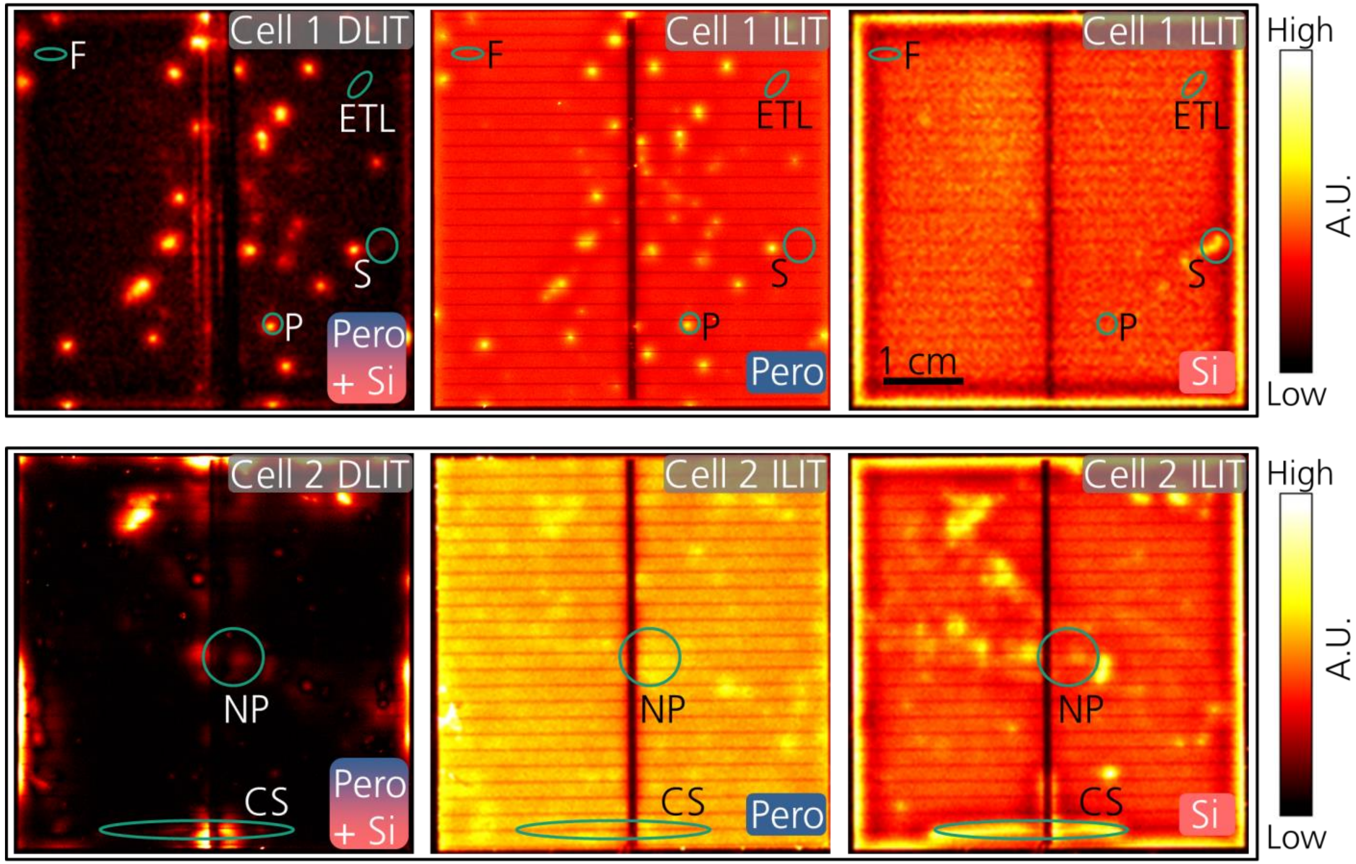
PLI Silicon sub cell

Analysis of Perovskite Silicon Solar Cells

Analysis of Sub Cell Inhomogeneities

Lock-in thermography for tandem solar cells

- Camera-based lock-in thermography with illumination at different wavelengths (470 nm, 655 nm, 950 nm) or external voltage



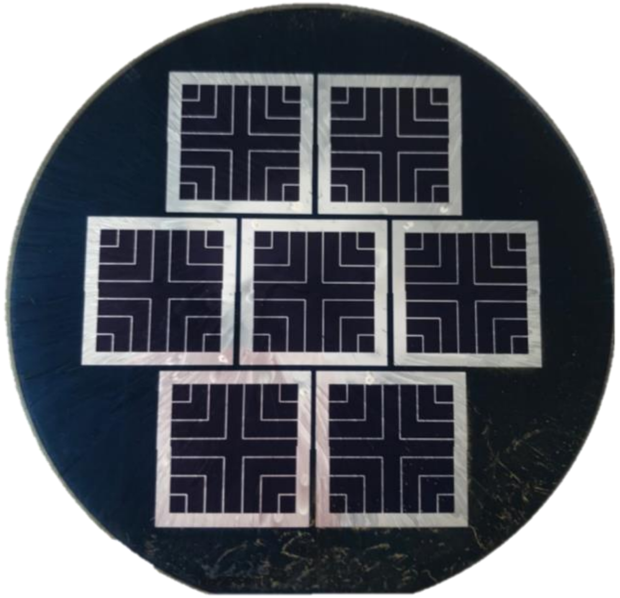
Fischer et al. Tandem PV-WS 2022

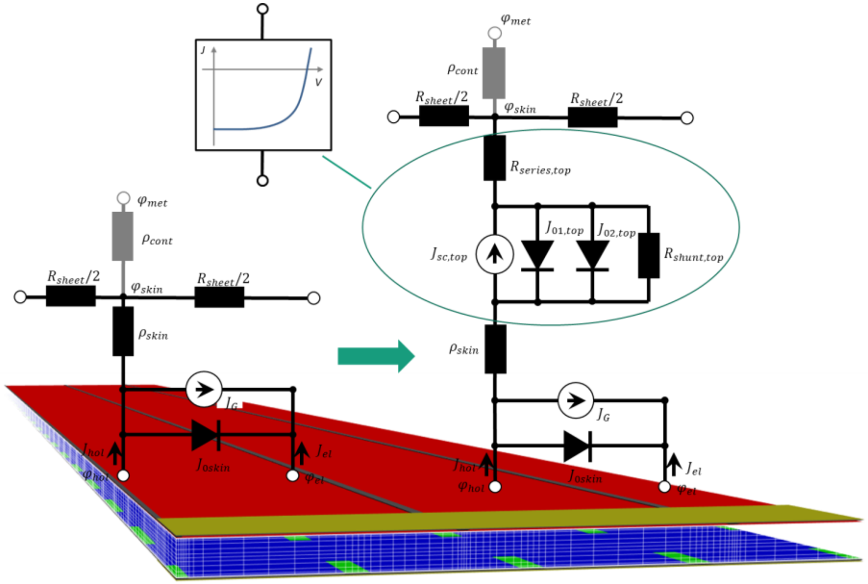
Analysis of Perovskite Silicon Solar Cells

Modeling for Cell Optimization

Quokka3 based modeling of lateral effects

- Edge losses
- Optimum contacting
- Local inhomogeneities and impact on global cell measurements

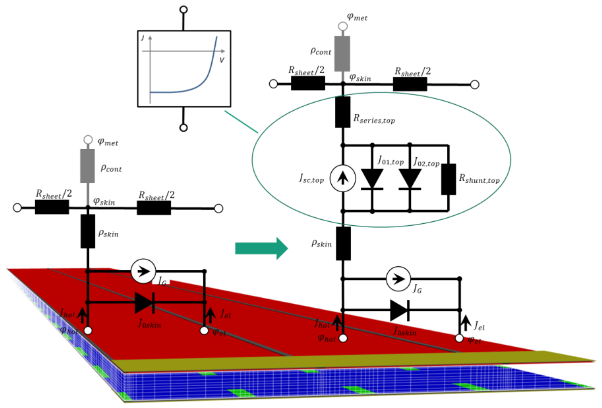




Fell, A., Schultz-Wittmann, O., Messmer, C., Schubert, M. C., & Glunz, S. W. (2022). Combining Drift-Diffusion and Equivalent-Circuit Models for Efficient 3D Tandem Solar Cell Simulations. *IEEE Journal of Photovoltaics*.

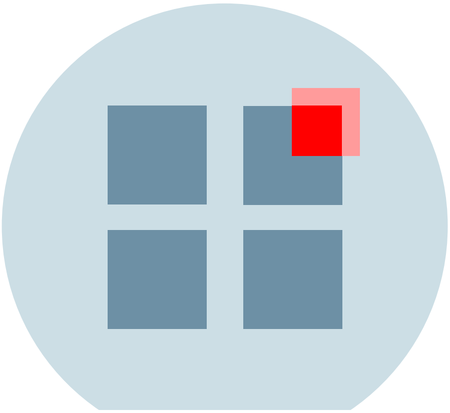
Analysis of Perovskite Silicon Solar Cells

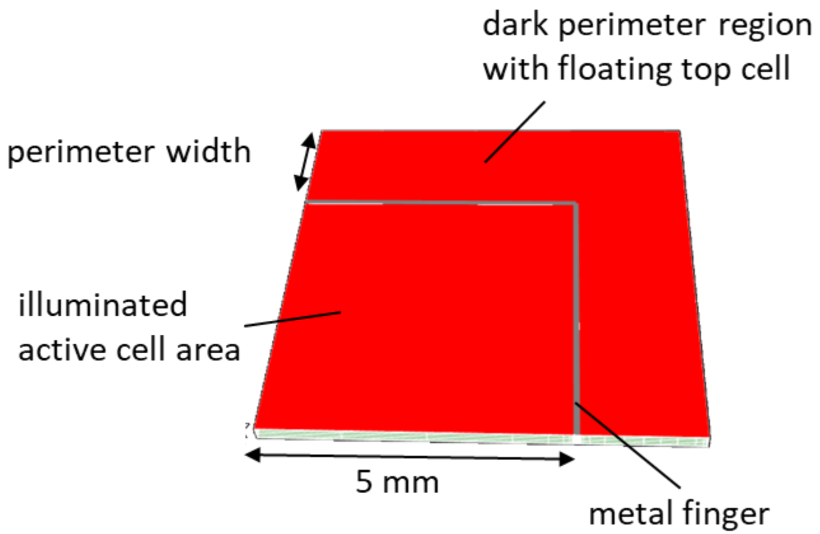
Modeling for Cell Optimization

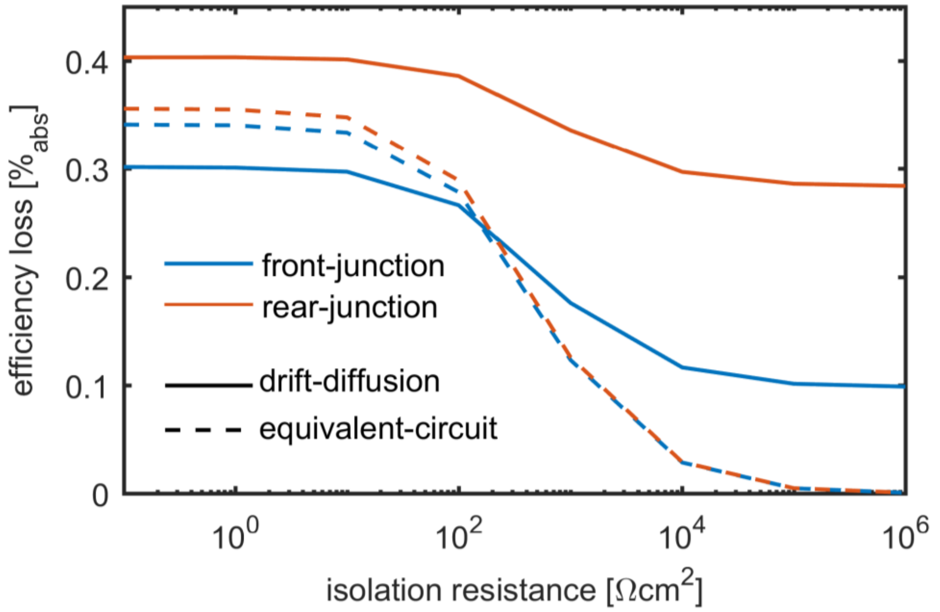


Quokka3 based modeling of lateral effects

- **Edge losses**
- Optimum contacting
- Local inhomogeneities and impact on global cell measurements





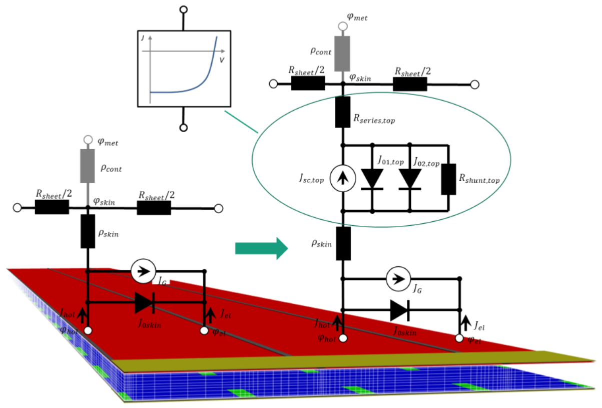


Analysis of Perovskite Silicon Solar Cells

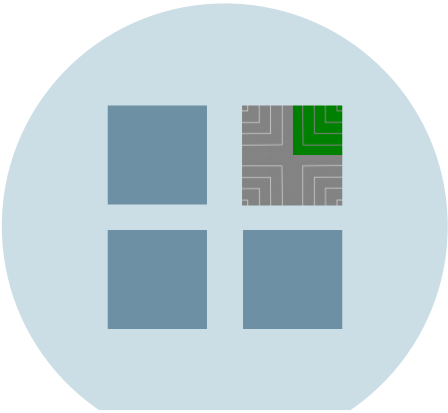
Modeling for Cell Optimization

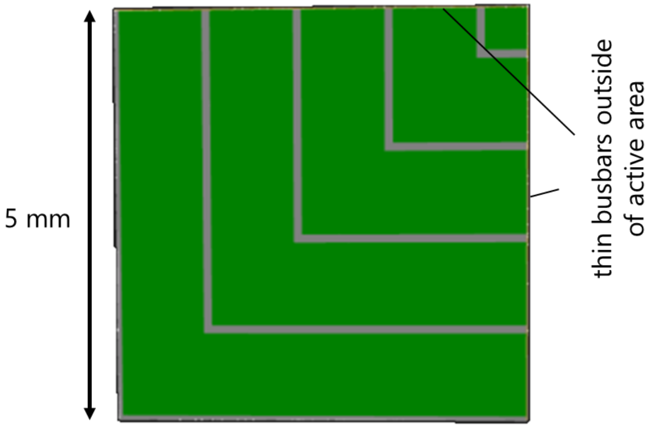
Quokka3 based modeling of lateral effects

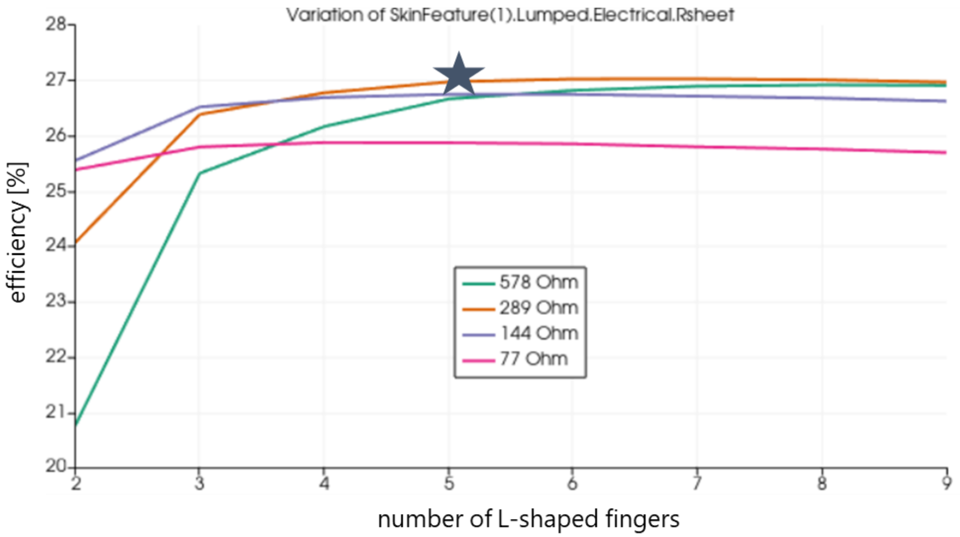
- Edge losses
- **Optimum contacting**
- Local inhomogeneities and impact on global cell measurements



Optimum: 27% @ 5 fingers and 20 nm TCO thickness

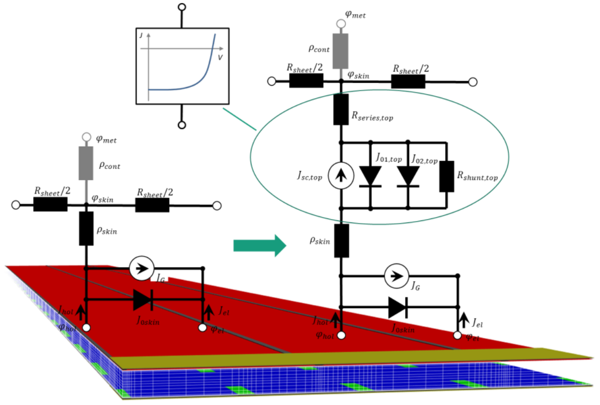






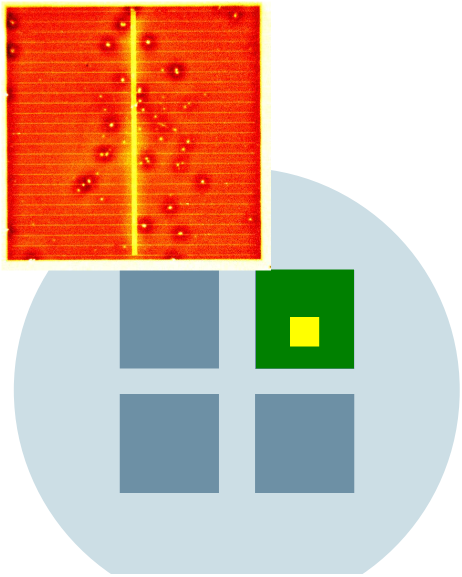
Analysis of Perovskite Silicon Solar Cells

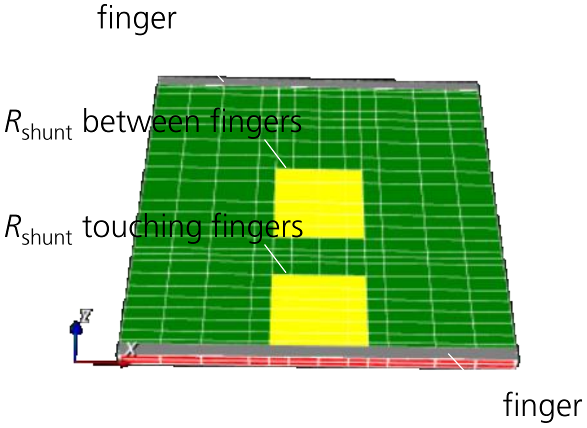
Modeling for Cell Optimization

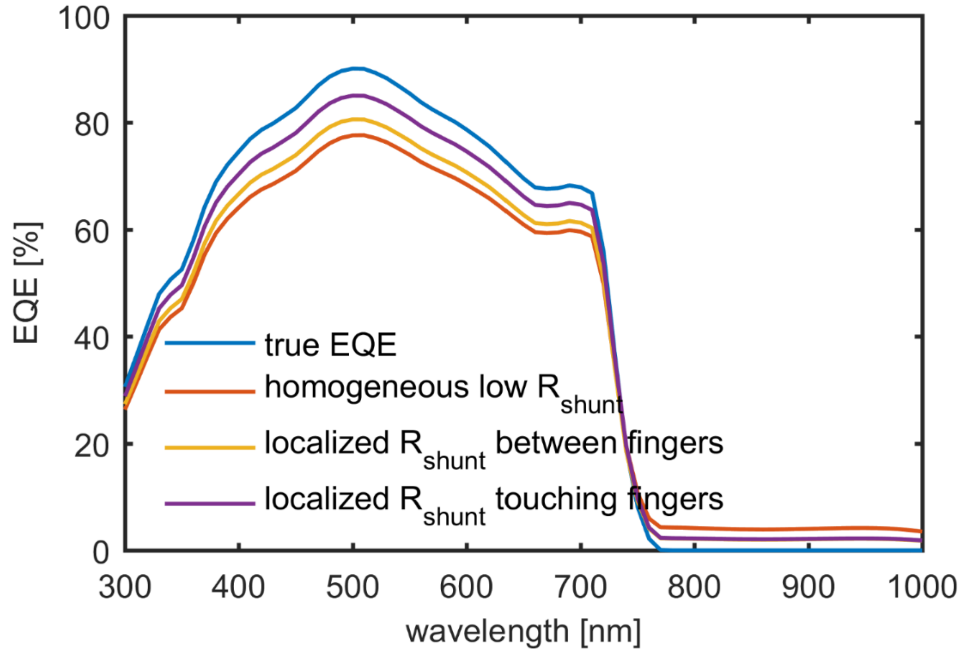


Quokka3 based modeling of lateral effects

- Edge losses
- Optimum contacting
- **Local inhomogeneities and impact on global cell measurements**







Fraunhofer ISE

Analysis of Perovskite Silicon Solar Cells

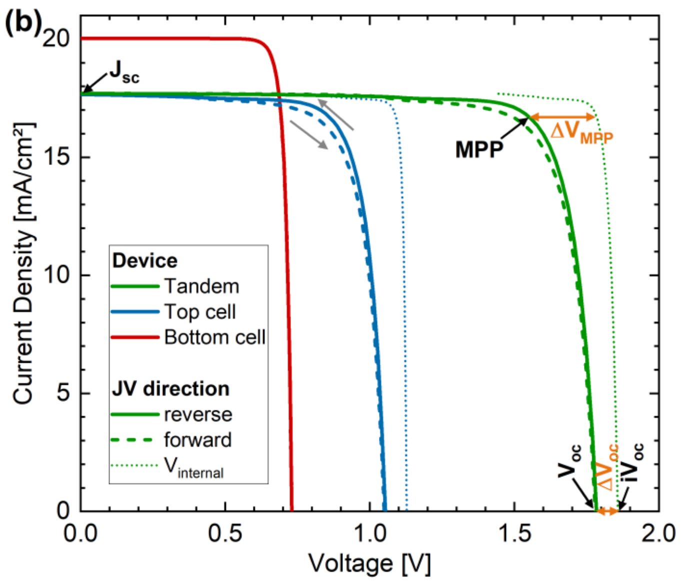
Modeling for Cell Optimization

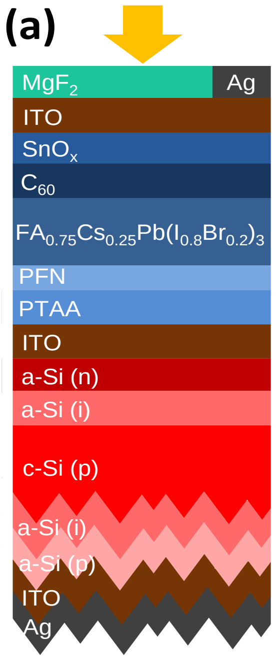
Quokka3 based modeling of lateral effects

- Edge losses
- Optimum contacting
- Local inhomogeneities and impact on global cell measurements

Sentaurus based modeling including detailed cell physics

- Transient effects
- Cell efficiency potential, technology comparisons
- Cell optimization





Messmer, C., Schön, J., Würfel, U., Schulze, P. S., Schubert, M. C., Bivour, M., ... & Hermle, WCPEC 8, 2022

Analysis of Perovskite Silicon Solar Cells

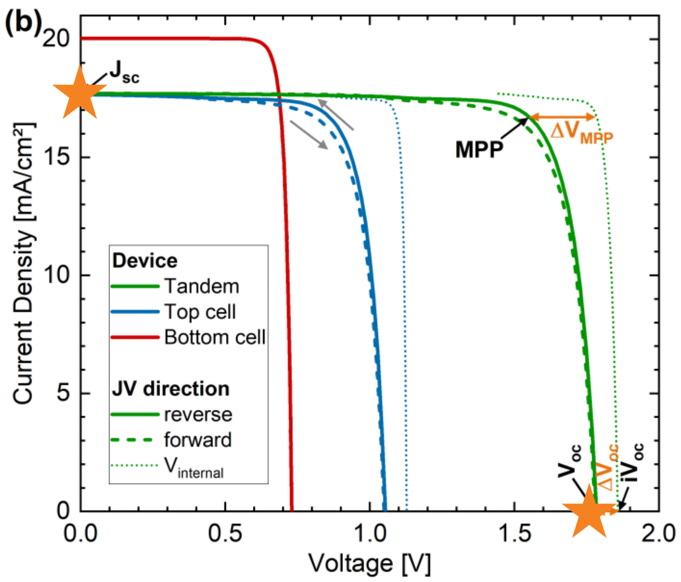
Modeling for Cell Optimization

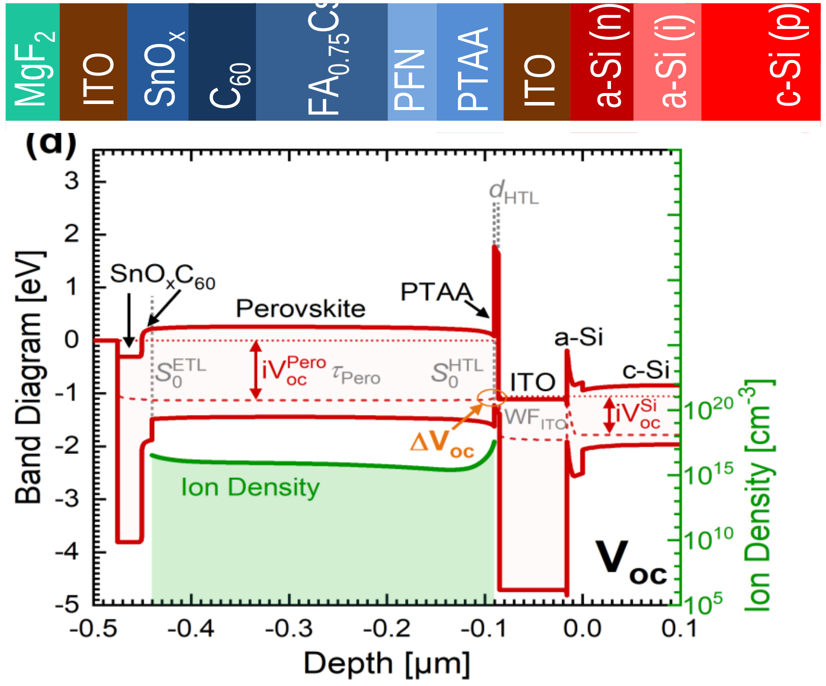
Quokka3 based modeling of lateral effects

- Edge losses
- Optimum contacting
- Local inhomogeneities and impact on global cell measurements

Sentaurus based modeling including detailed cell physics

- Transient effects
- Cell efficiency potential, technology comparisons
- Cell optimization





Fraunhofer CSP

Fraunhofer-Center für Silizium-Photovoltaik CSP

Fraunhofer CSP

Metrology for Thin Layers

Metrology for Thin Layers

Sample Handling

Glovebox

Thin films can be sensitive to moisture and oxygen. Usually, nitrogen-filled gloveboxes are used for perovskite cell preparation.

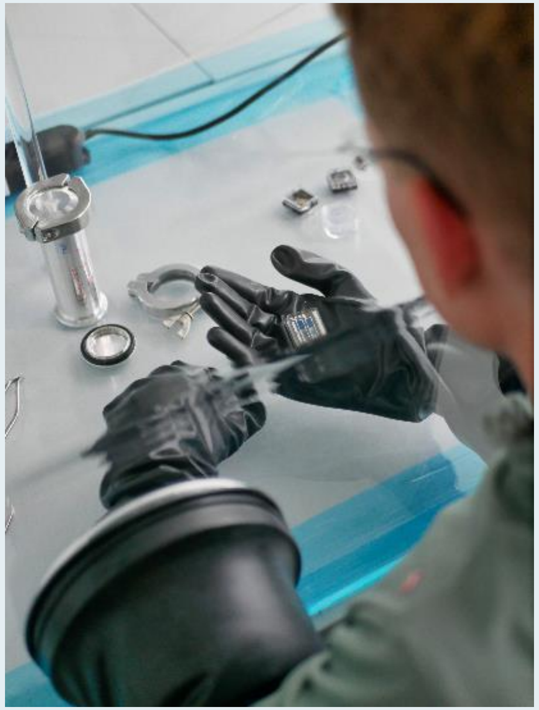
Problem

- Oxidation and hydrolysis can occur
- Electronic surface properties change and analytical results can be affected

Approach

- Sample transfer protocol for perovskites and organic layers
- Shipment in air-tight containers
- Handling and sample-preparation in a glovebox
- Inert transfer system for transport between glovebox and XPS/UPS or ToF-SIMS

Glovebox with port for inert sample transfer to analytic facilities



Fraunhofer ISE

Metrology for Thin Layers

Sample Preparation

Focused Ion Beam

Problem

- Sample preparation is a crucial step and often limits the quality of the measurement
- Traditional (mechanical) methods are slow, not site-specific, sensitive to failures and produce small samples only

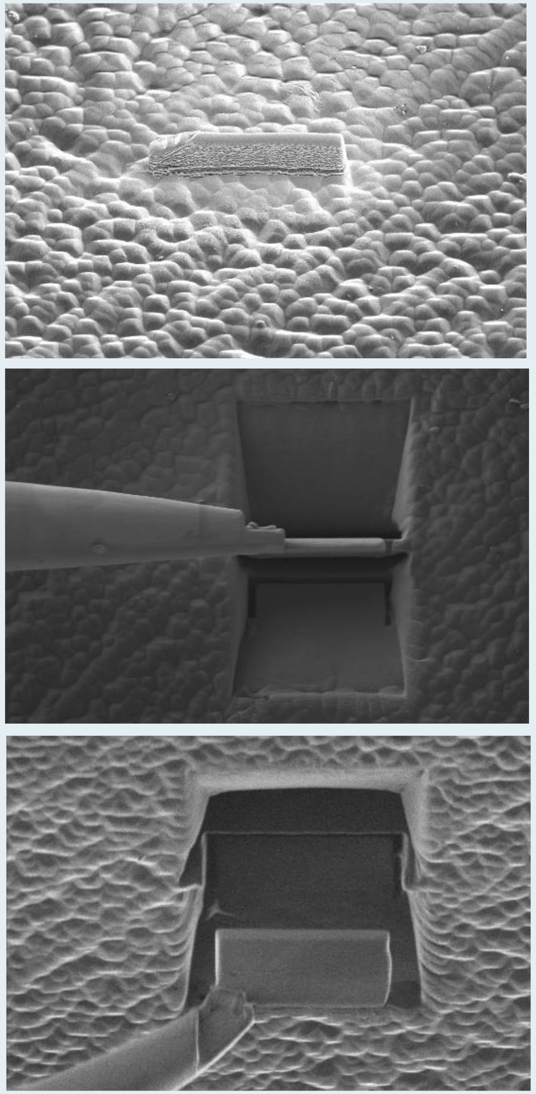
Approach

- Defects are localized by SEM
- Region of interest is cut out by FIB and lifted out with a micromanipulator
- Ion-milling with low-voltage Ar ions to minimize surface damage or implantation

Application

- Site-specific preparation of grain boundaries or defects with nm-resolution
- Preparation of electron-transparent TEM lamellae (< 100 nm)
- 3D imaging (slice-and-view) in SEM

Lift-out of a TEM lamella



Metrology for Thin Layers

Microscopical methods

TEM

Due to the sensitivity of the materials, sample preparation and TEM analysis is especially challenging.

Sample preparation

- FIB cuts perpendicular to the surface
- Direct deposition on electron-transparent substrates

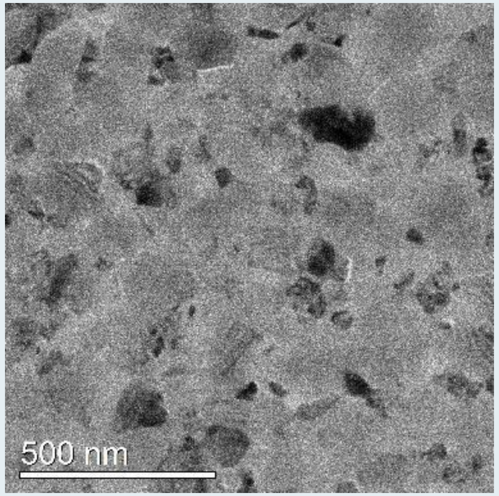
Measurements

- TEM and STEM for direct imaging of electron transparent samples
- Electron diffraction for analysis of crystalline materials
- EDX for quantitative elemental composition and mapping

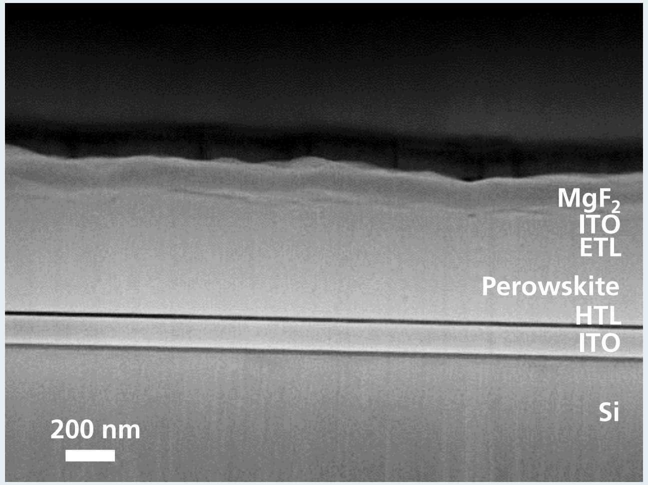
Application

- Investigation of layer stacks (side view), e.g. on a large sample's edges
- Direct imaging of layers (top view) for determination of internal structure
- Determination of layer thickness with nm-resolution

Direct imaging by electron microscopy



TEM of a 50 nm thick perovskite layer



STEM on a multilayer system

Metrology for Thin Layers

Surface Analysis

Photoelectron spectroscopy

XPS is a surface-sensitive technique for quantitative chemical analysis.

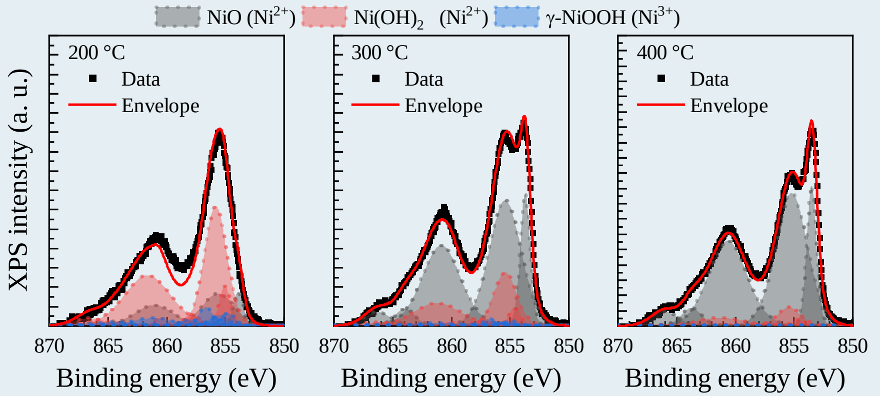
Approach

- Inert sample transfer to the XPS system to avoid air contact
- Determination of chemical elements and their oxidations states
- Coupling with sputter process for depth profiles
- Lateral resolution 50 µm, depth resolution 5 nm

Application

- Layer analysis for detailed understanding of a material's composition
- Monitoring of chemical reactions: Changes in a metal's oxidation states (e.g. during thermal conversion of a precursor)
- Detection of impurities (e.g. silicon from a sealant)

XPS monitors the conversion of a nickel oxide precursor



Detail spectra of the core level Ni $2p_{3/2}$ transitions of wet-chemically deposited and annealed NiO_x layers.

Metrology for Thin Layers

Surface Analysis

ToF-SIMS

Time-of-flight mass spectrometry is a sensitive method for detection of elements and molecules.

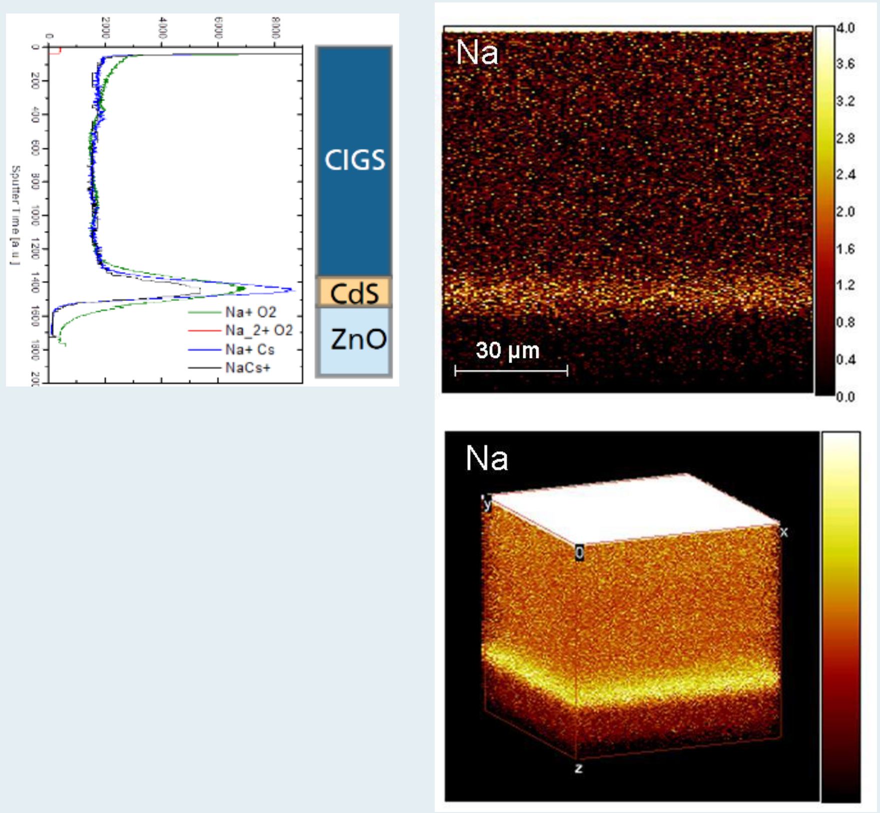
Approach

- Inert transfer to the ToF-SIMS system avoids sample contamination
- Analysis with ppb-sensitivity (10^{15} atoms per cm^3), lateral resolution of 0.2–5 µm and depth resolution of 10 nm
- Quantitative analysis by comparison with standards

Applications

- Identification of elements and chemical compounds
- 3D reconstruction by combination of depth profil and 2D mapping

3D reconstruction of Na within a CIGS sample by ToF-SIMS



Metrology for Thin Layers

Optical methods

HSI

Hyperspectral imaging a fast non-contact method for detecting lateral uniformity of optical properties.

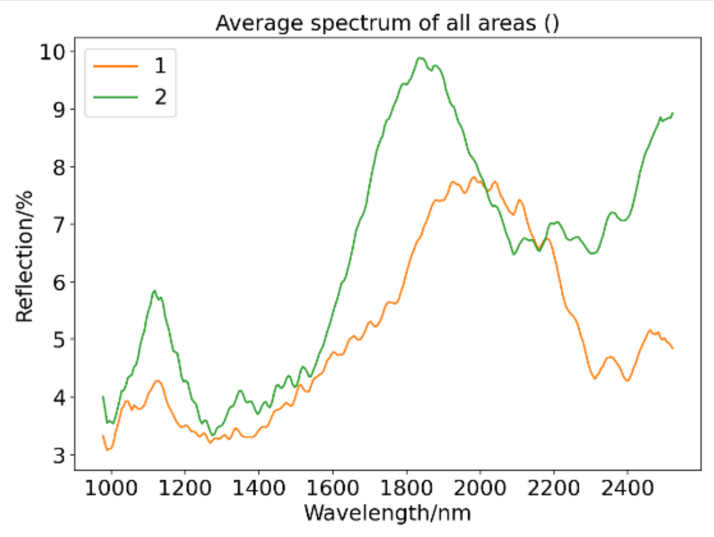
Approach

- Hyperspectral optical imaging in VNIR (400–1000 nm) or SWIR (1000–2500 nm) range (reflection)
- Data analysis using automated machine learning algorithms (classification, clustering …) and data visualization (spectra, false-color RGB, color-overlays)

Applications

- Detection of lateral non-uniformities in a sample by spectral fingerprint
- Detection of sample-to-sample variations
- Suitable for in-line applications

Optical spectra of two samples from the same production line



Contact

David Adner
Diagnostics and Metrology
Tel. +49 345 5589 277
Fax +49 345 5589 5999
david.adner@csp.fraunhofer.de

Fraunhofer Center for Silicon Photovoltaics CSP
Otto-Eissfeldt-Straße 12
06120 Halle (Saale)
Germany
www.fraunhofer.de

Fraunhofer CSP

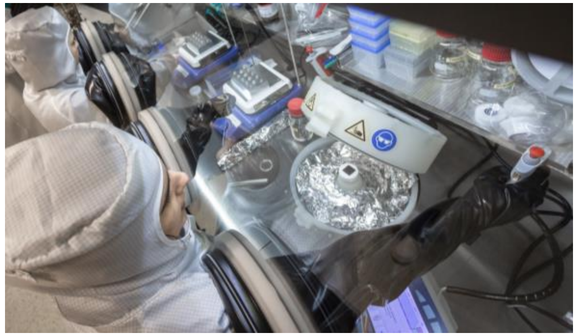
Fraunhofer-Center für Silizium-Photovoltaik CSP

Fraunhofer ISE

Processing of Pero-Si-tandem solar cells

PeroLab – Wetchemical Processing

Processing Infrastructure @ISE

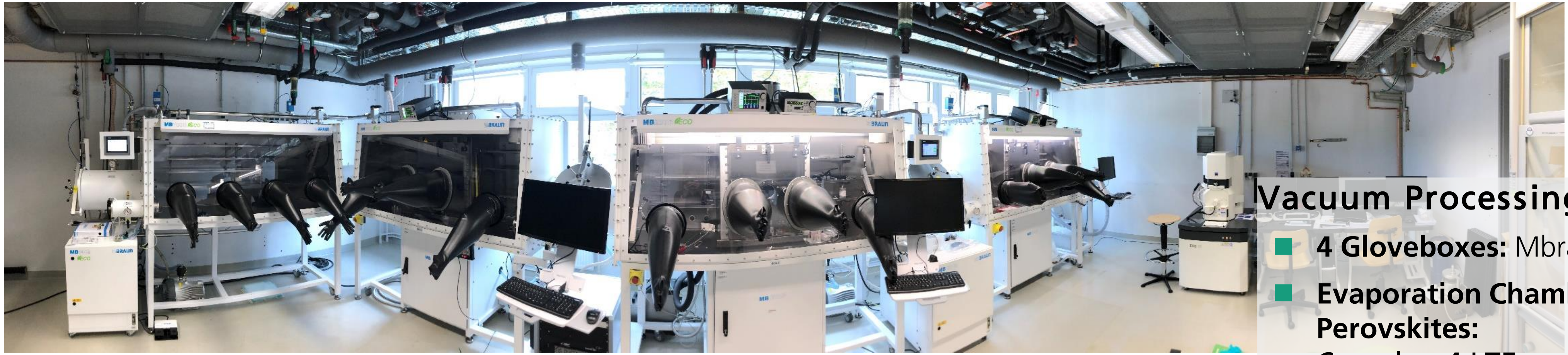


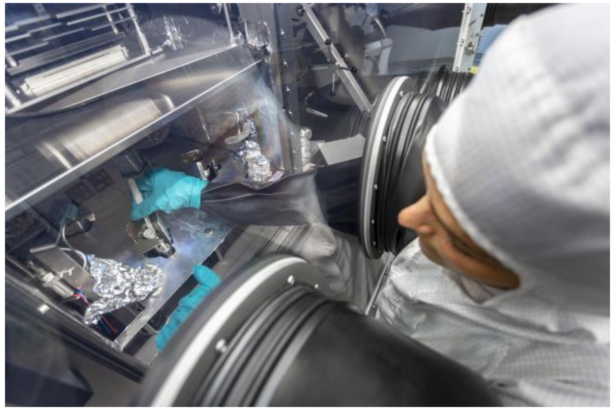
Wetchemical Processing

- **4 Gloveboxes with separated atmospheres:**
  GS Glovebox Systemtechnik
- **Precision Scales**
- **Stirring Equipment**
- **Hot Plates**
- **Spin-Coater**
- **Slot-Die Coater (from Feb 2023)**
- **UV/Ozone Chamber**

PeroLab – Vacuum&Hybrid Processing

Processing Infrastructure @ISE





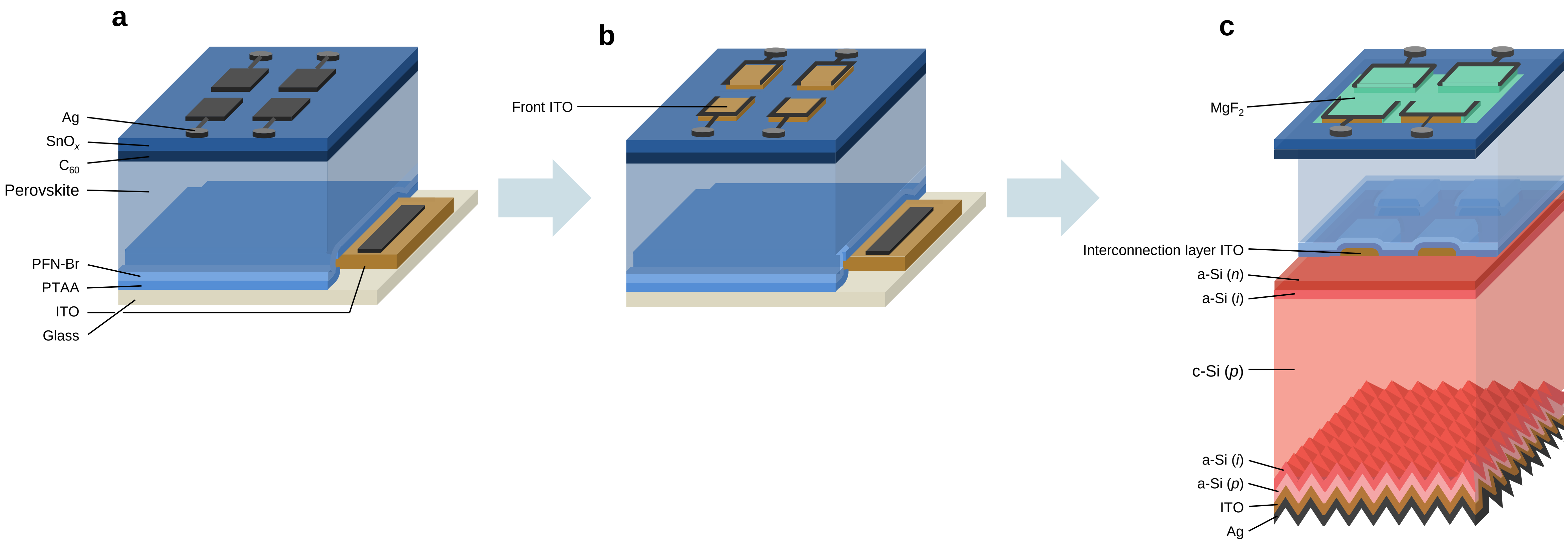
Vacuum Processing

- **4 Gloveboxes:** Mbraun
- **Evaporation Chamber for Perovskites:** Creaphys 4 LTE sources
- **Evaporation Chamber for Metals & Metal Oxides:** Creaphys E-Gun / 2 Thermal Sources
- **Evaporation Chamber for Contact Materials & Organics:** Creaphys 2 LTE / 2 Thermal Sources
- **Atomic Layer Deposition:** Arradiance
- **Spin-Coater** for Hybrid Route

From Single-Junction to Tandem Solar Cells

Main Focus on Monolithic 2-Terminal Perovskite Silicon Tandem Solar Cells

Opaque S-J PSC | **Semitransparent S-J PSC** | **Monolithic 2T Pero-Si Tadem**



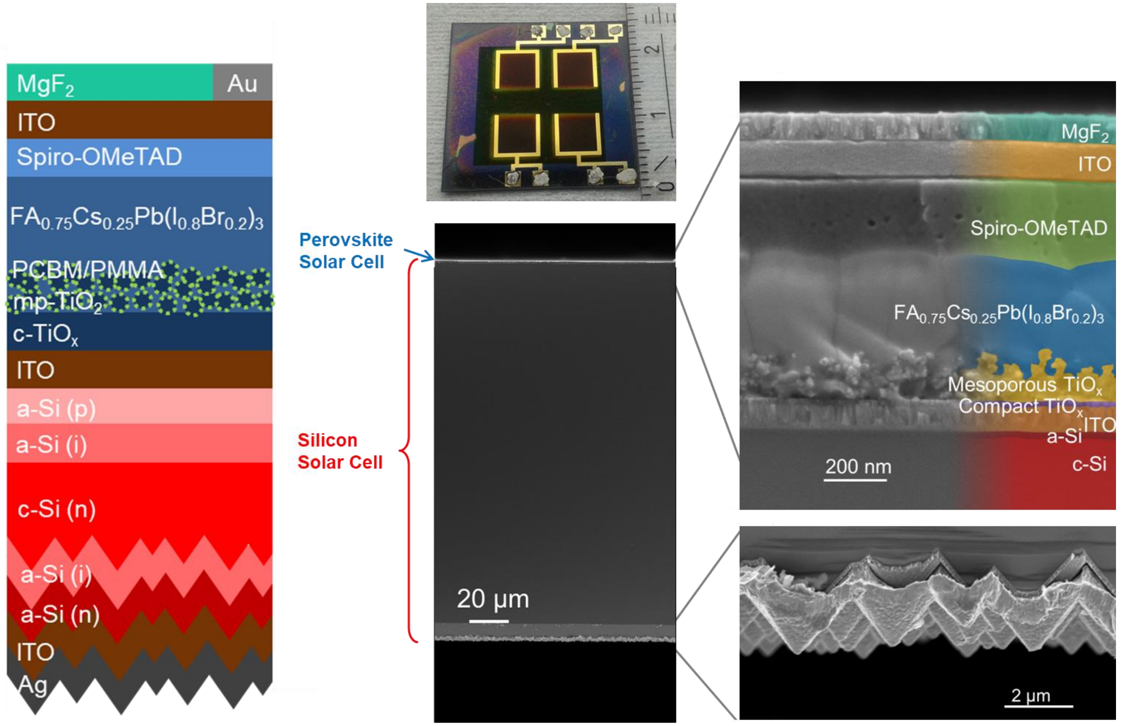
From Dissertation P.S.C. Schulze, 2020, University of Freiburg

Fraunhofer ISE

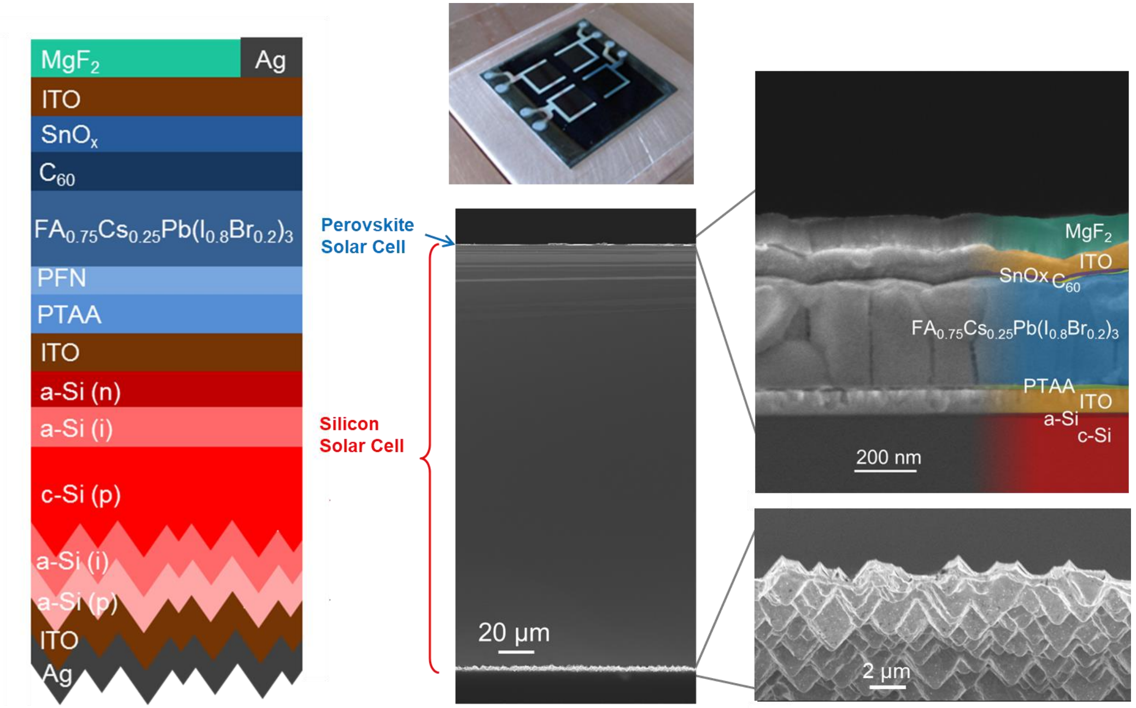
Tandem Device Architectures

Examples Realized at ISE

n-i-p Tandem



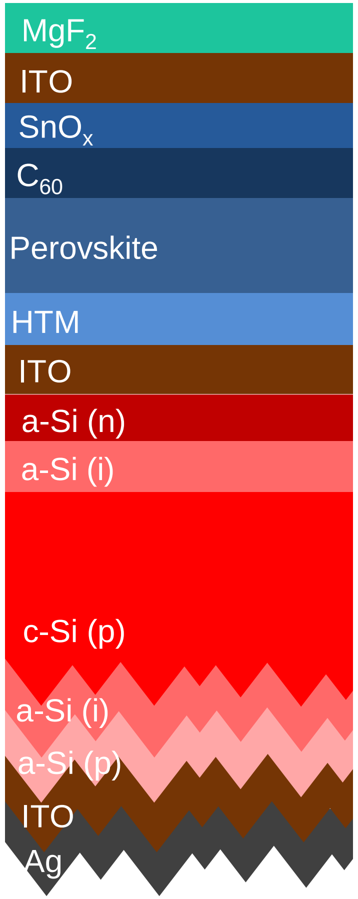
p-i-n Tandem

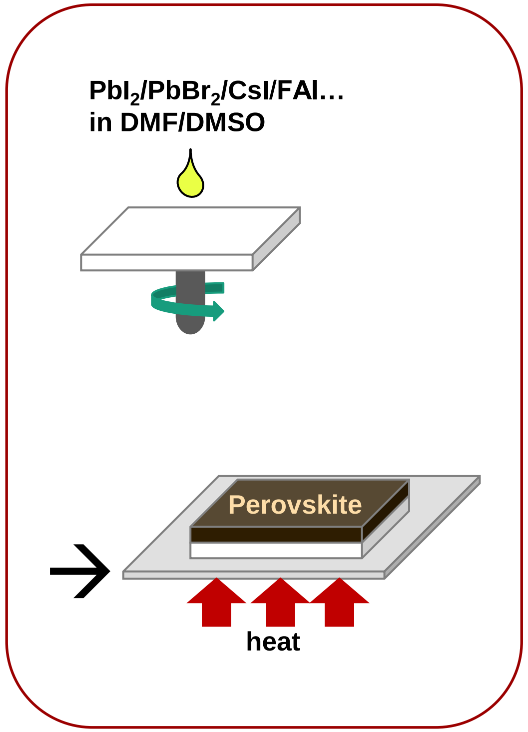


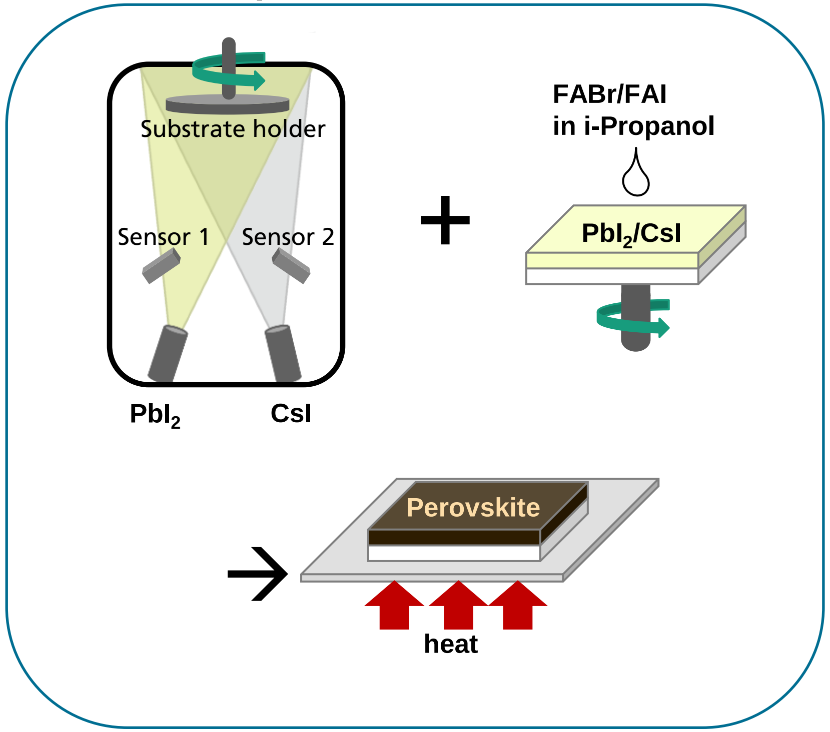
PSCO Poster, P.S.C. Schulze, 2019

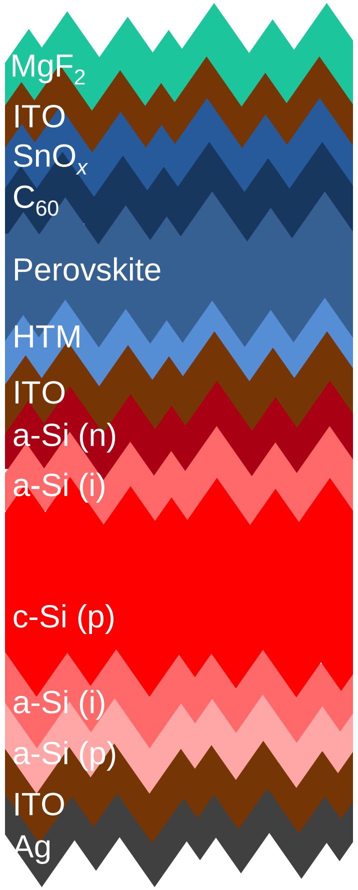
Pero-Si Tandem Processing Routes

Main Routes for Top-Cell Processing in PeroLabs









P. S. C. Schulze, et al. Solar RRL 4 (7), 2000152 (2020)
P. S. C. Schulze, et al. Thin Solid Films 704, 137970 (2020)

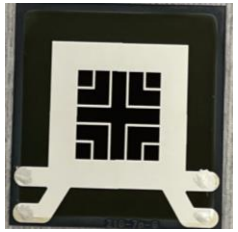
Pero-Si Tandem Upscaling

From Substrate to Full Wafer Processing

25 mm

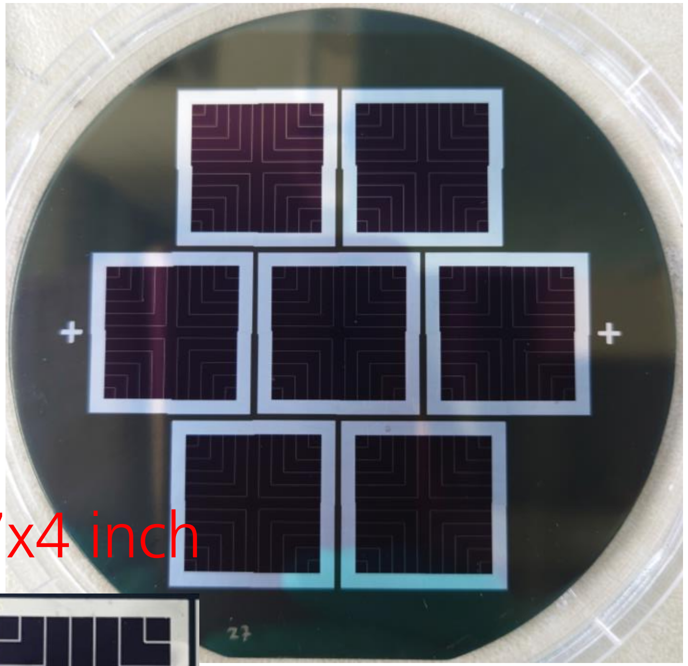
5 mm

25 mm



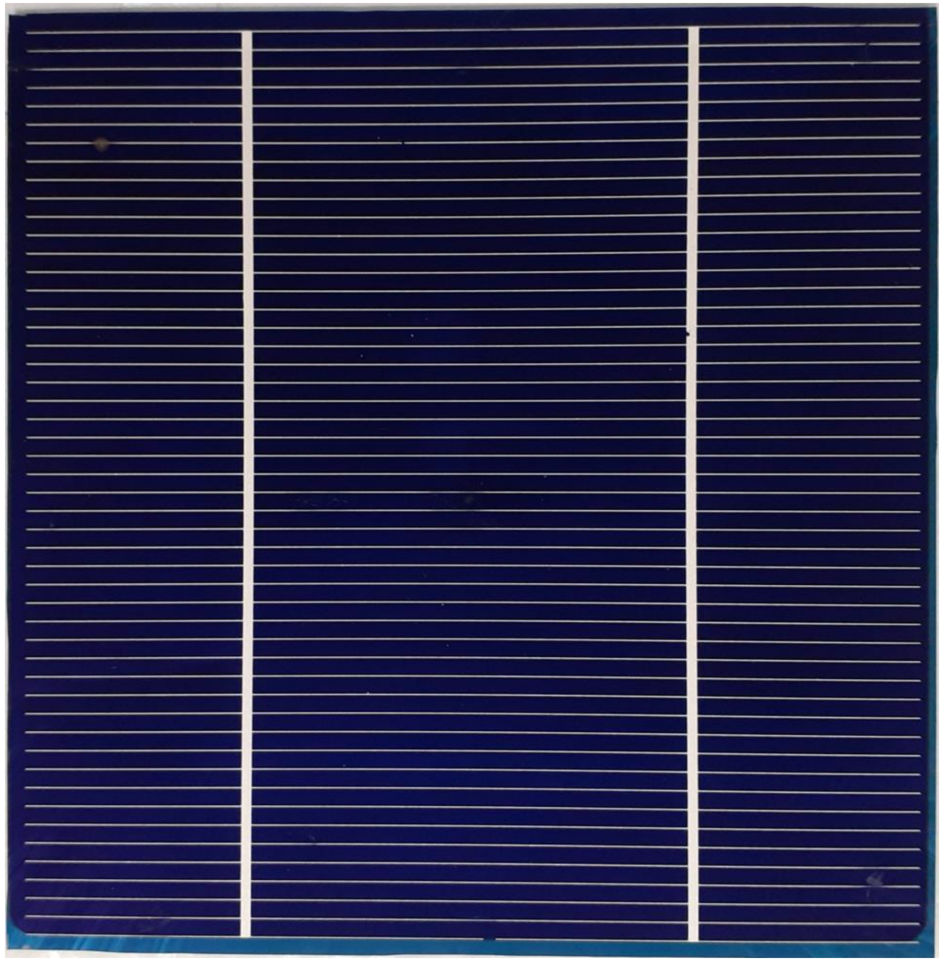
10 mm

7x4 inch



20 mm

102 mm



102 mm

Fraunhofer ISE

Contact

Dr. Patricia S. C. Schulze
Neuartige Solarzellenkonzepte
Photovoltaik – Forschung

Tel. +49 761 4588-5955
patricia. schulze@ise.fraunhofer.de

Perovskite and Perovskite-Tandem PV at Fraunhofer ISE & Fraunhofer CSP

How to work with us

- https://www.viperlab-kep.eu/infrastructure.asp
  https://www.viperlab-kep.eu/infrastructure.asp?i=10&t=FRAUNHOFER__Solar_Cell_Manufacturing_eamp;_Characterization

FRAUNHOFER Solar Cell Manufacturing & Characterization

Solar cell manufacturing & characterization

- High efficiency silicon bottom cells
- Vacuum and wet chemical processing of layers for perovskite tandem solar cells
- Metallisation concepts
- Electrical and optical analyses of perovskite silicon tandem cells and precursers
- High resolution analyses down to the nano scale

Organisation : FRAUNHOFER

Perovskite and Perovskite-Tandem PV at Fraunhofer ISE & Fraunhofer CSP

What is a promising proposal?

- You have promising samples with some pre-characterization which you would like to bring for in-depth analysis
  - The samples are stable enough that they survive the traveling

or

- You have a good idea for sample processing or analysis

- The work contains a new and exciting aspect
- There is a clear path towards further exploitation of the results, e.g. in joint publications

FRAUNHOFER - Solar Cell Manufacturing & Characterization

Dr. Martin Schubert
Head of Quality Assurance, Characterization and Simulation
martin.schubert@ise.fraunhofer.de

More information at
Viperlab.eu
FULLY CONNECTED **VI**RTUAL AND PHYSICAL
PEROVSKITE PHOTOVOLTAICS **LAB**