Triple-Junction Solar Cells: Sub-Cell *IV* Curve and Current Matching Point Analysis

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Introduction

- j_{SC} obtained from integrated measured *EQE*s can be misleading
  - Parallel resistance (R_P) effects → dependence on applied bias voltage[1]
  - Dynamic effects in perovskite → dependence on measurement conditions[2]
  - → Current matching situation should not be determined from measured *EQE*s
- Spectrometric characterization allows for investigation of current matching situation and sub-cell properties (hysteresis, R_P, breakthrough effects)[3,4]

Spectrometric Characterization for Triple-Junction Solar Cells[5]

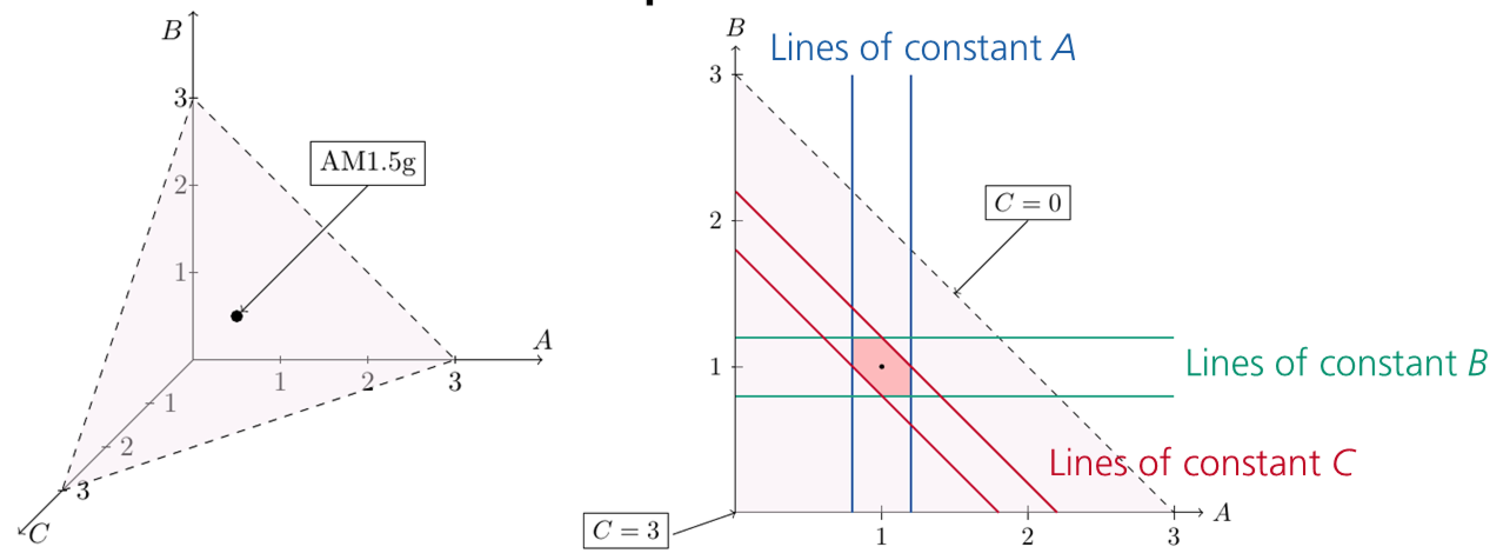
Principle of Spectrometric Characterization

- Determining *IV* parameters for systematically varied spectral conditions[3]
- Only relative spectral responses needed to calculate the different spectra
- Realized using a solar simulator with 20 individually adjustable LEDs[6]

From Dual-Junction to Triple-Junction Solar Cells[3,5]

	Dual-Junction Case	Triple-Junction Case
Definition of spectral conditions	$j_{top}^{sim} = (1+z)\, j_{top}^{AM1.5g}$ $j_{bot}^{sim} = (1-z)\, j_{bot}^{AM1.5g}$	$j_{top}^{sim} = A\, j_{top}^{AM1.5g}$ $j_{mid}^{sim} = B\, j_{mid}^{AM1.5g}$ $j_{bot}^{sim} = C\, j_{bot}^{AM1.5g}$
AM1.5g condition	$(1+z) = (1-z) = 1$	$A = B = C = 1$
Effective irradiance	$(1+z) + (1-z) = 2$	$A + B + C = 3$
Geometry	Line of measurement	Plane of measurement

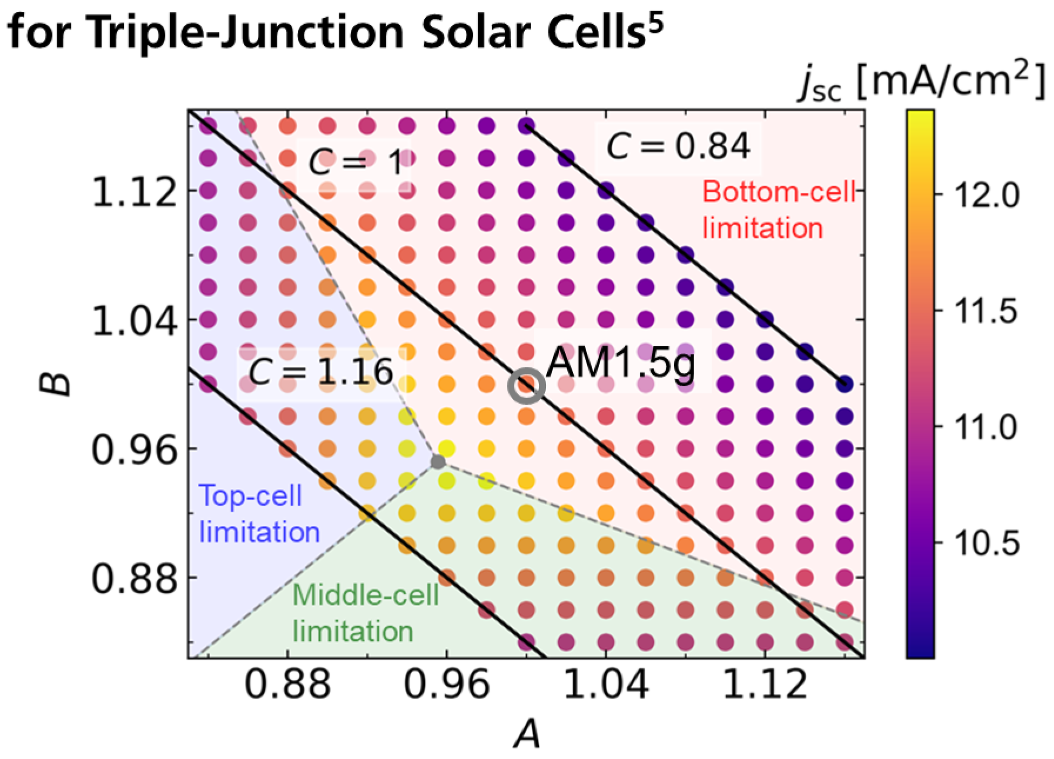
Plane of Measurement for Triple-Junction Solar Cells[5]



(left) Plane of measurement $A + B + C = 3$ with $A, B, C > 0$ and (right) projection on the A-B plane with a hexagonal measurement area (here: variation of A, B and C between 0.8 and 1.2)

Representation of Results for Triple-Junction Solar Cells[5]

- Measurement area can be divided into three sections in each of which another sub-cell is limiting the current
- Bottom-cell is limiting at the AM1.5g condition ($A = B = C = 1$) in this example (III-V on silicon triple-junction solar cell[7])



j_{SC} obtained from spectrometric characterization

Relevance for Realistic Operation Conditions[5]

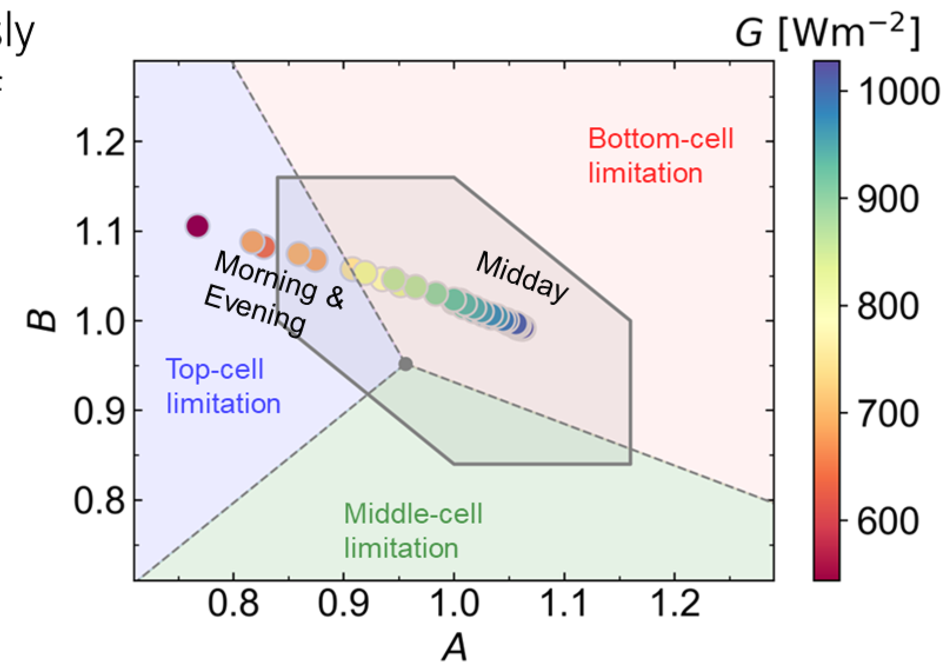
- Spectral conditions continuously change outdoors → change of current limiting sub-cell
- Outdoor conditions:

$$j_{top}^{out} = A'\, j_{top}^{AM1.5g}$$
$$j_{mid}^{out} = B'\, j_{mid}^{AM1.5g}$$
$$j_{bot}^{out} = C'\, j_{bot}^{AM1.5g}$$

- Irradiance changes outdoors → $A' + B' + C' \neq 3$
- Projection on plane of measurement possible:

$$\begin{pmatrix} A \\ B \\ C \end{pmatrix} = \frac{3}{A'+B'+C'} \begin{pmatrix} A' \\ B' \\ C' \end{pmatrix}$$

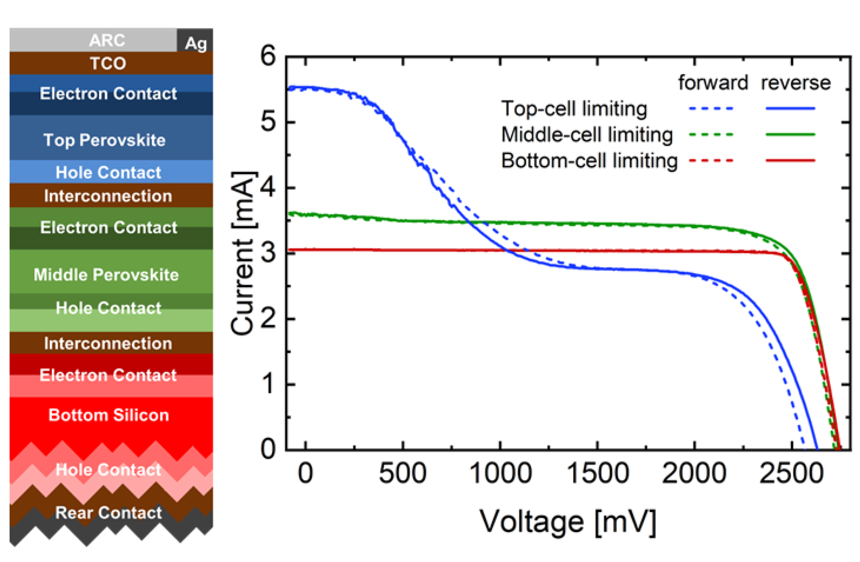
- Realistic outdoor conditions can be reproduced indoors



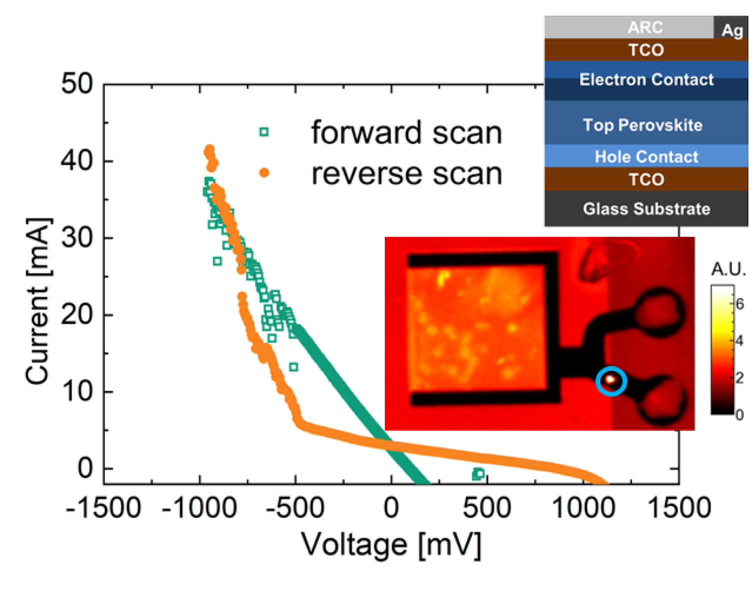
Variation of spectral conditions and current limiting sub-cell within one day (May 18, 2022, Freiburg/ Germany), metric parameters obtained for a III-V on Si triple-junction solar cell[7] from measured outdoor spectra

Investigation of Sub-Cell *IV* Curves → Breakthrough Effects in Perovskite on Silicon Triple-Junction Solar Cells[8]

- During an *IV* scan the limiting sub-cell operates under negative bias[8,9]
- Low breakthrough voltage of perovskite solar cells (shunts appear under metal contacts)
- Breakthrough effect visible in *IV* curve of triple-junction solar cells when top cell is limiting



Sketch of a perovskite on silicon triple-junction solar cell and IV curves recorded under different spectral conditions leading to different sub-cell limitations



Breakthrough of a single-junction top-cell: IV curves up to -1 V, thermography image showing a shunt near the metal contact

Conclusion

- ➢ Spectrometric characterization extended from dual-junction solar cells to triple-junction solar cells
- ➢ Realistic outdoor conditions can be reproduced → use of spectrometric characterization as input for energy yield analysis possible
- ➢ Investigation of *IV* curves under different sub-cell limitations gives access to sub-cell behavior invisible under reference spectral conditions (parallel resistance, hysteresis, breakthrough effects)

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7 Cariou et al., Nat. Energ. 3 (4), 2018, 326-333, DOI: 10.1038/s41560-018-0125-0
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This work was supported by the German Federal Ministry for Economic Affairs and Climate Action (BMWK) under contract number 03EE1132A (RIESEN) and by European Union's Horizon research and innovation program under grant agreement No 101075725 (TRIUMPH)