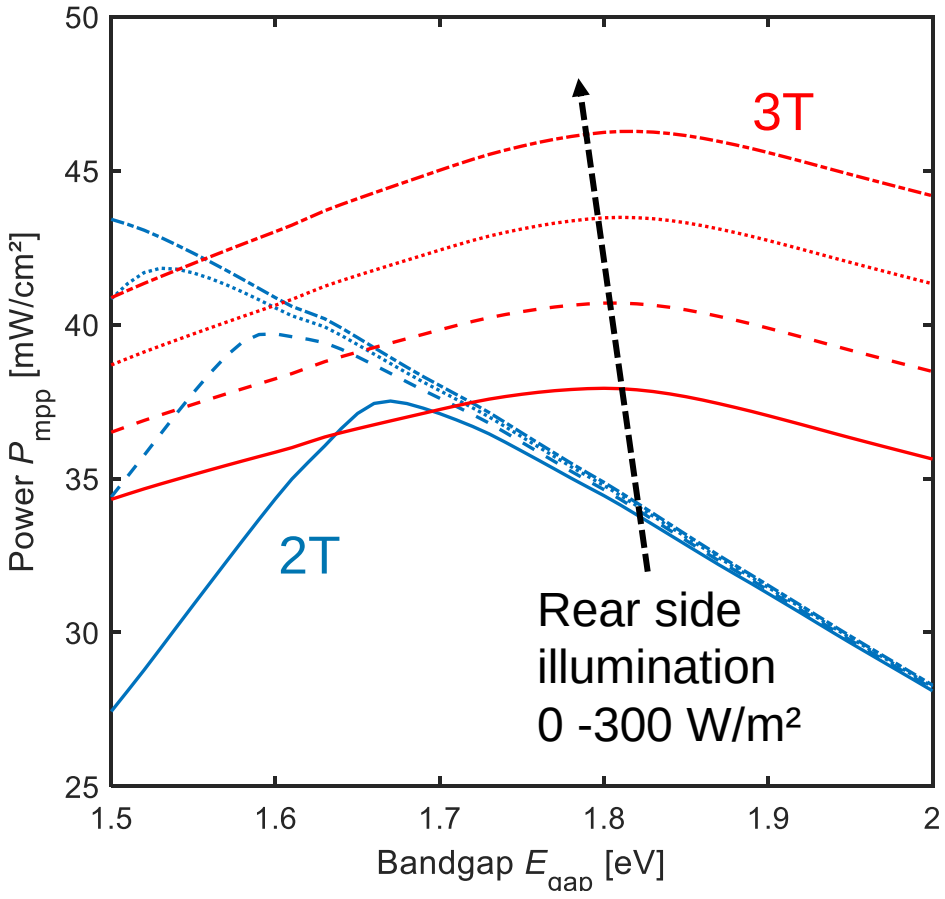


From 3T tandem solar cells to 2T tandem modules – advantages and disadvantages

H. Schulte-Huxel[1], M. Köntges[1,], R. Witteck[1,5], S. Blankemeyer[1],, M. Rienäcker[1], M. Gholipoor[2,3], U. W. Paetzold[2,3], R. Peibst[1,4]

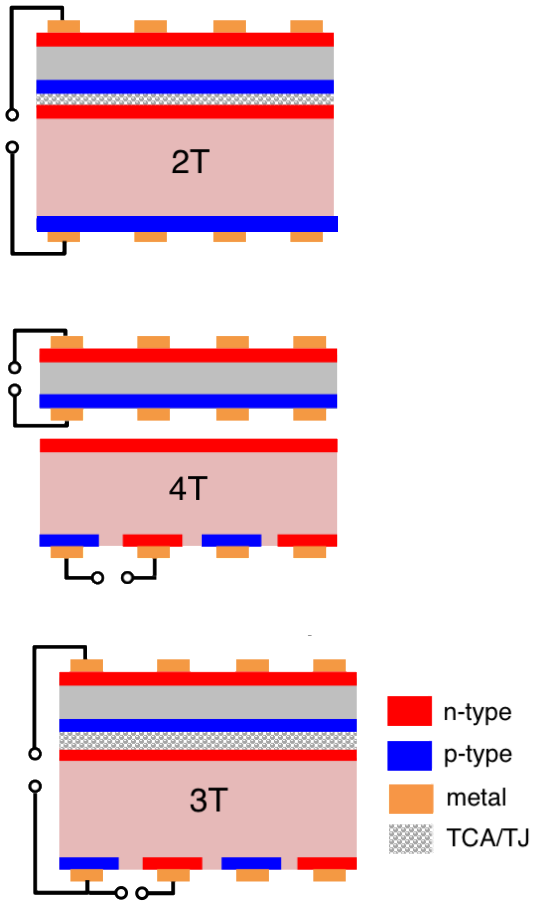
[1]Institute for Solar Energy Research Hamelin (ISFH)
[2]Light Technology Institute (LTI), Karlsruhe Institute of Technology (KIT)
[3]Institute of Microstructure Technology (IMT), KIT
[4]Institute for Electronic Materials and Devices, Leibniz University Hannover (LUH)
[5] now at National Laboratory of the Rockies, formerly National Renewable Energy Laboratoy (NREL)

Impact of terminal configuration

- 2TT (two terminal tandem): series connected subcells
  ➔ similar module integration as single junction solar cells
  ➔ requires current matching associated with mismatch losses

- 4TT: parallel connected subcells and strings
  ➔ seperate contact structure and interconnection of subcell strings with shading losses due to intermediate contacts
  ➔ no current mismatch losses

- 3TT: parallel/series connected subcells
  ➔ “a bit” more complex module integration
  ➔ no current mismatch losses, requires voltage matching with typically lower losses



Schemes from:
M. Schnabel et al., Sustainable Energy Fuels, 4, 549–558, 2020

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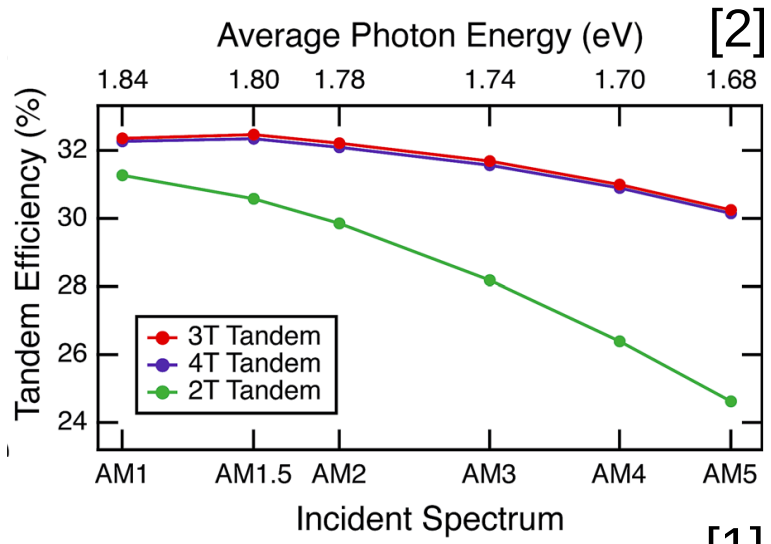
- 3TT: parallel/series connected subcells
  ➔ more complex module integration
  ➔ no current mismatch losses, requires voltage matching with typically lower losses

- 3TT and 4TT solar cells outperform 2TT devices

- 3TT solar cells have equal or higher efficiency and energy yield potential than 4TT devices[1,2]

[2]



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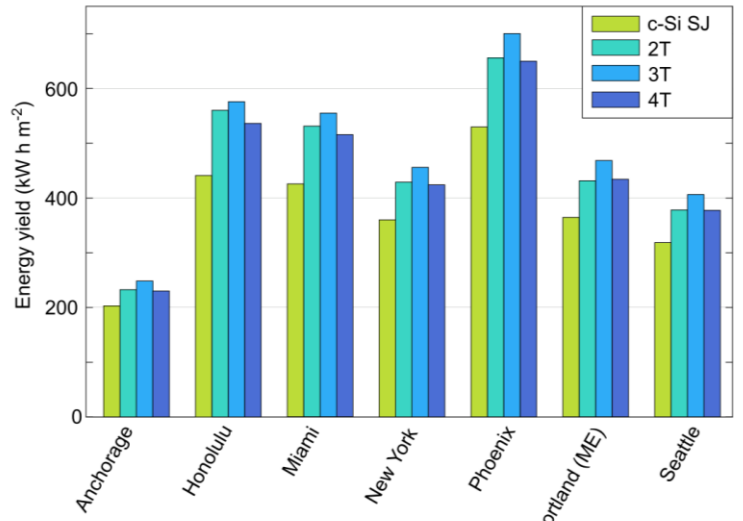
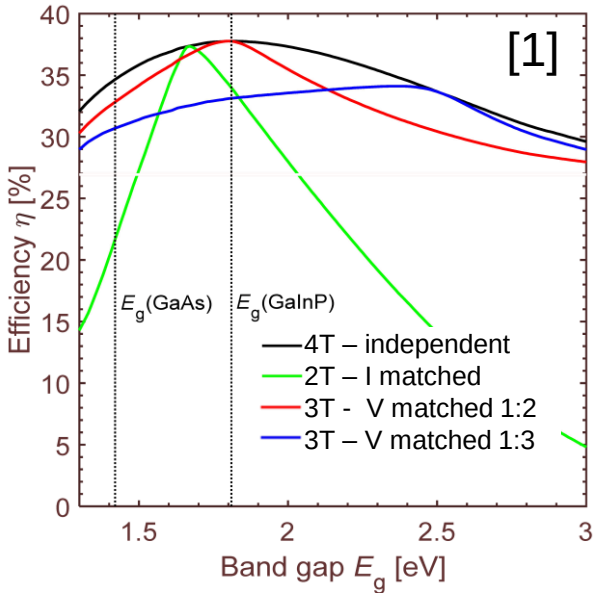


[1] F. Gota et al., Joule 4, 2387–2403, 2020
[2] E. Warren et al., Sustainable Energy Fuels 2, 1141–1147, 2018

In modules - impact of current vs. voltage matching

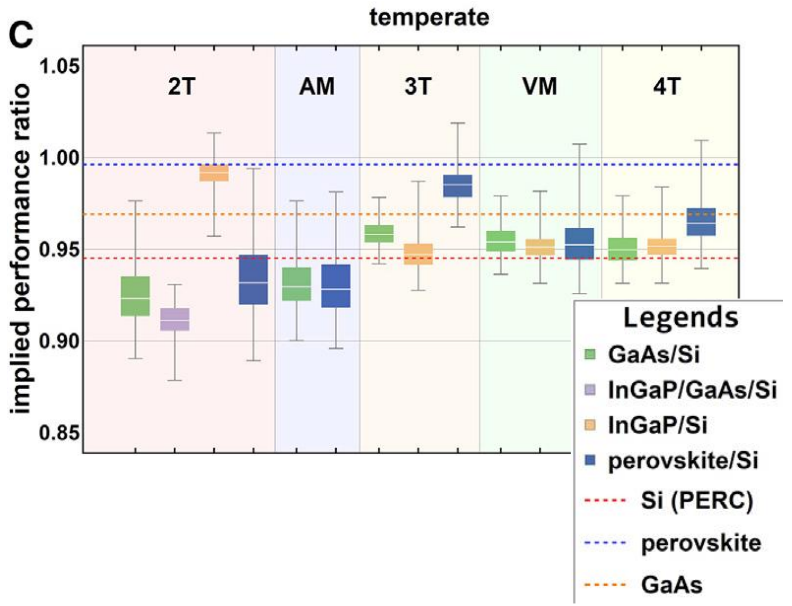


[4]

ANNUAL EFFICIENCY CALCULATED FOR DIFFERENT BAND GAP ENERGIES WITH THE SPECTRAL TMY DATA FOR DENVER, CO, USA

Number of terminals	1.42 eV	1.67 eV	1.81 eV
2	20.4%	35.4%	33.0%
3	31.6%	35.4%	36.3%
4	33.3%	35.9%	36.4%

[5]



Voltage matching shows enhanced robustness against:

- Spectral variations[1,3] with potential benefit on energy yield[4,5]
- Non-perfect bandgap match[1,2]
  ➔ Freedom of choice of top cell bandgap e.g. for higher stability
- Change in current variation of subcells ➔ bifacial application
- Degradation of subcells

[1] H. Schulte-Huxel, D. J. Friedman, and A. C. Tamboli, IEEE J. PV 8(5),1370–1375, 2018.
[2] K. VanSant et al., iScience, 9, 104950, 2022,
[3] J.M. Gee, *Solar Cells* 24, 147-155, 1988.
[4] H. Schulte-Huxel et al., JPV 8(5),1376-1383, 2018.
[5] H. Liu et al., Cell Reports Physical Science 1, 100037, 2020

In modules - impact of current vs. voltage matching

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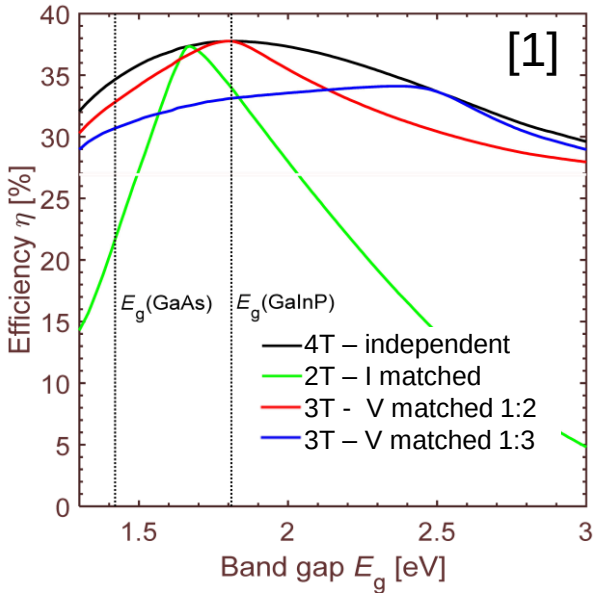

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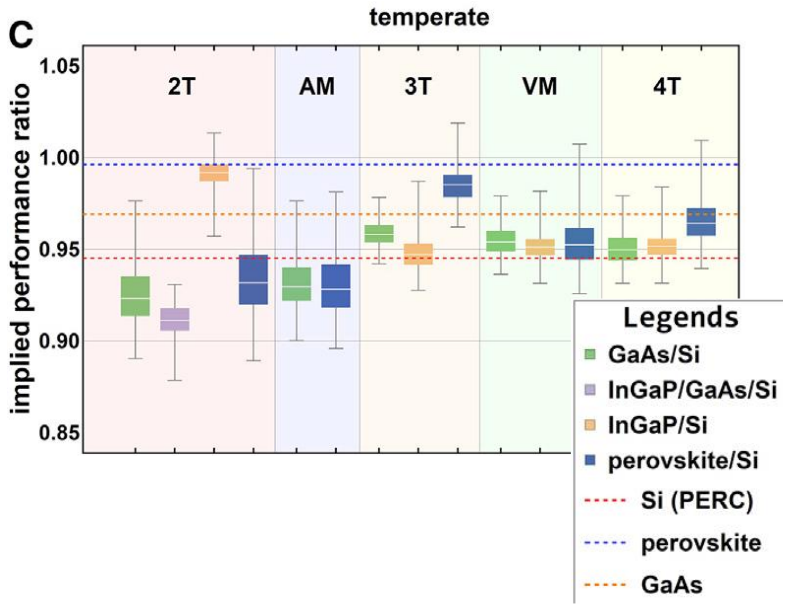

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Freedom of choice of top cell bandgap for higher stability

- $(Cs_{0.15}FA_{0.85}PbI_3)$ **(1.52 eV)**
- $(Cs_{0.05}MA_{0.10}FA_{0.85}Pb(I_{0.90}Br_{0.10})_3$ **(1.58 eV)**
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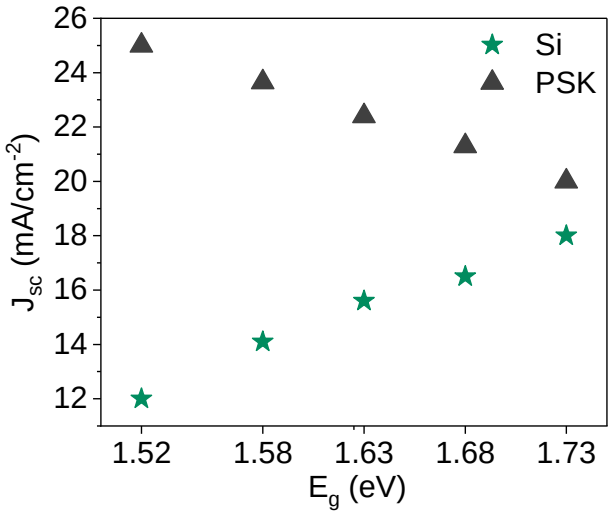

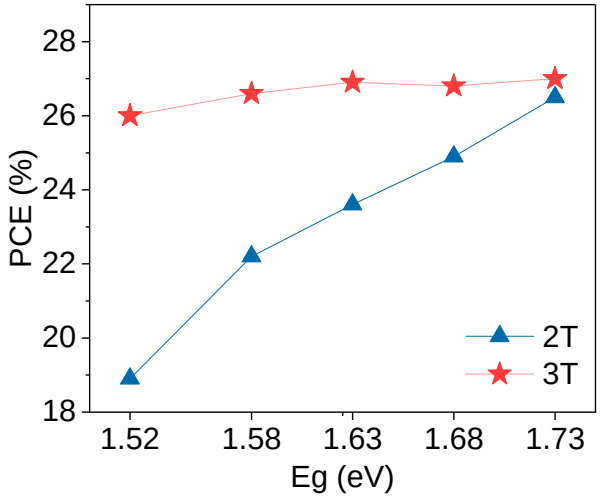

- Reduction of Br-content improves stability of perovskite solar cells[1]
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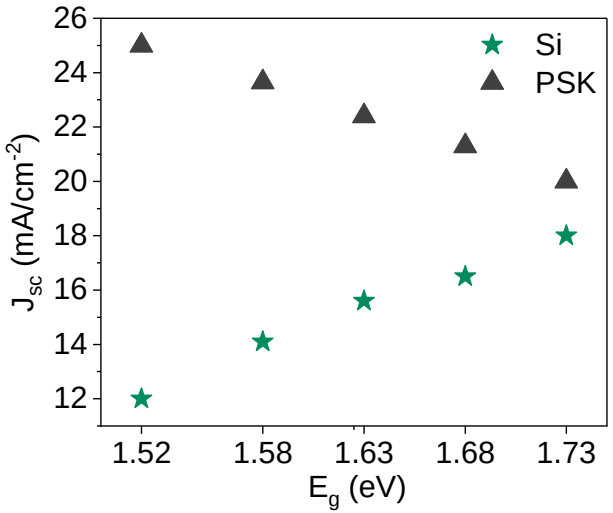

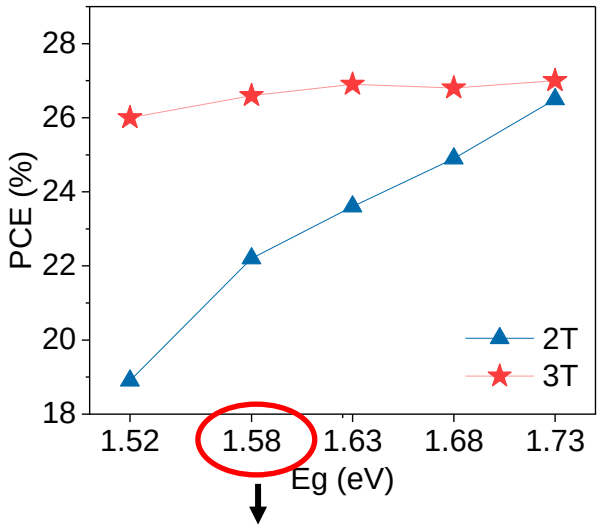

Champion cell

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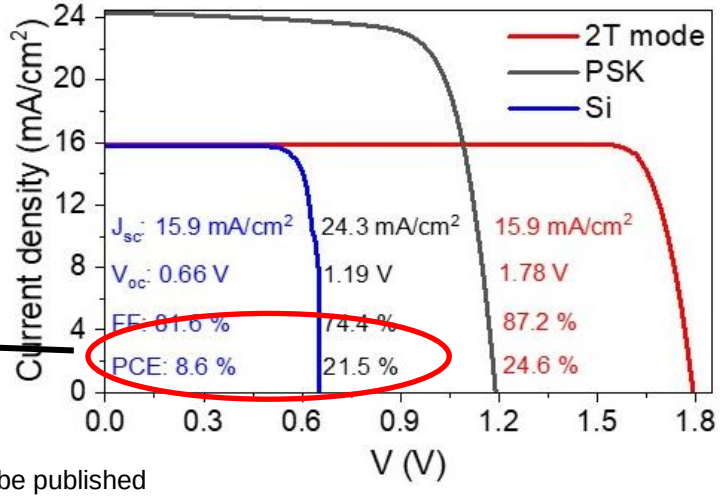
2T (TR measurement)		3T measurement
24.6	<	30.1



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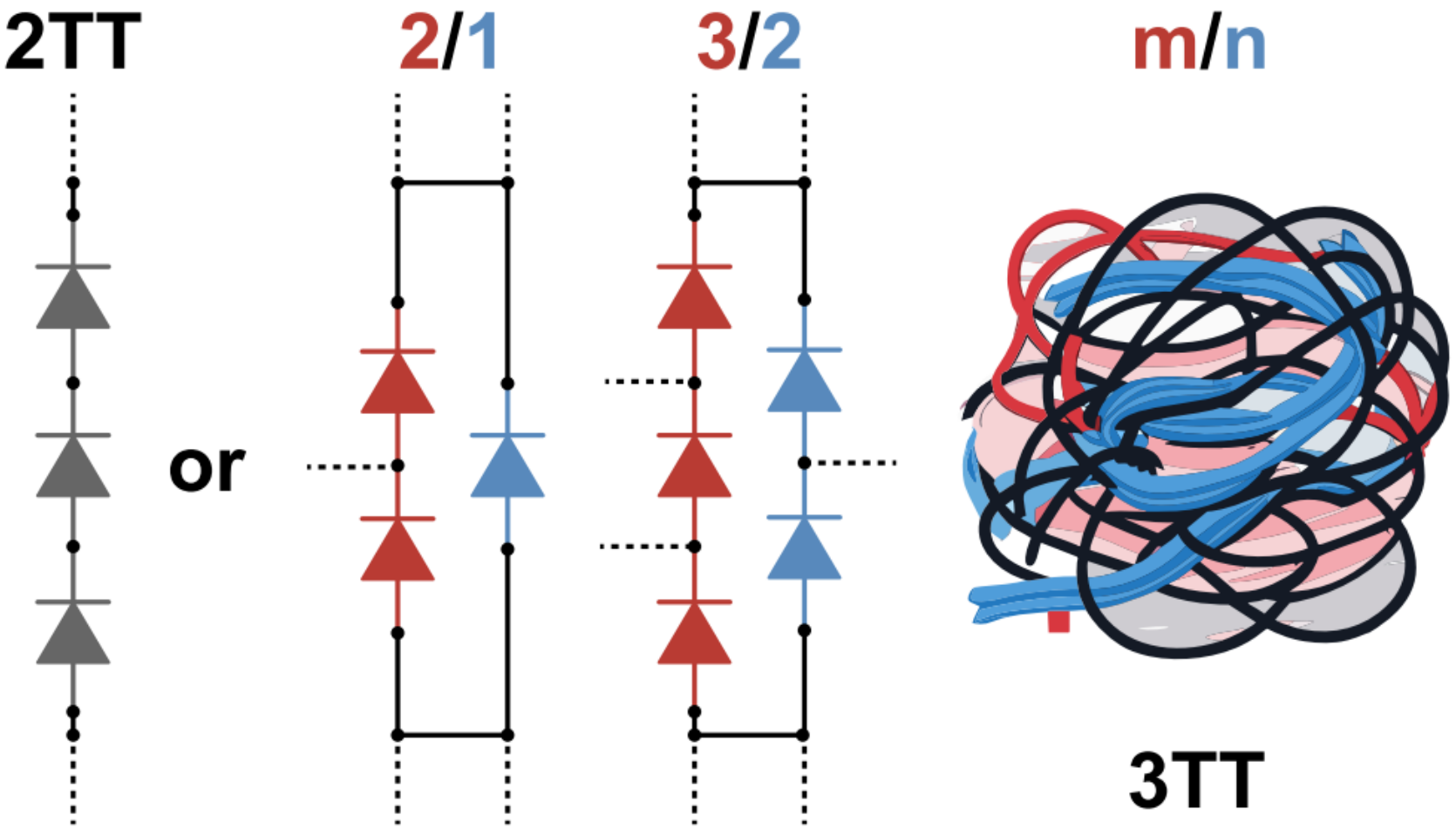
Interconnection of 3T cells???



M. Kikelj et al., Joule 8 1-20, 2024

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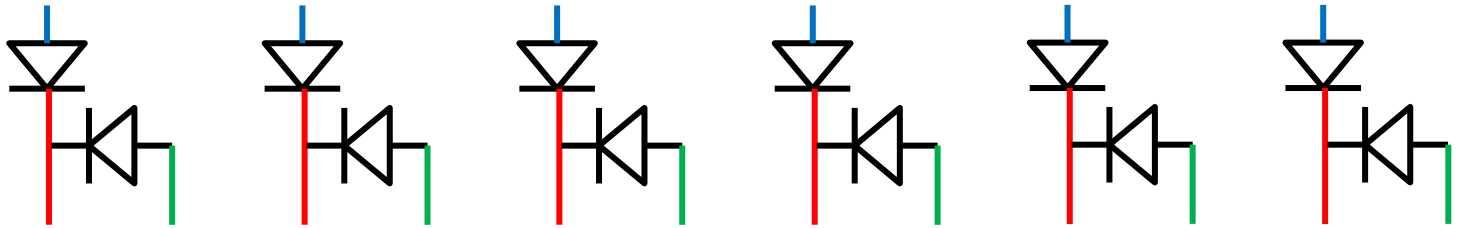
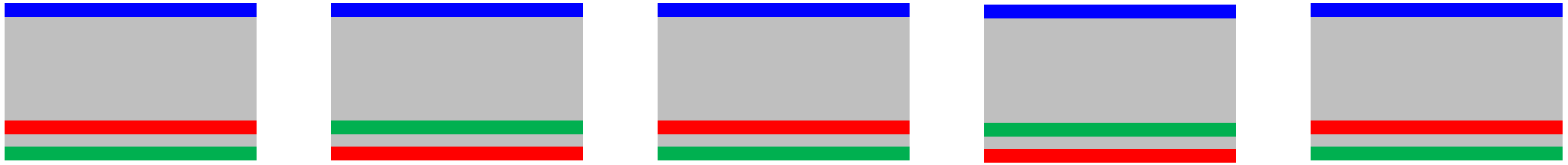
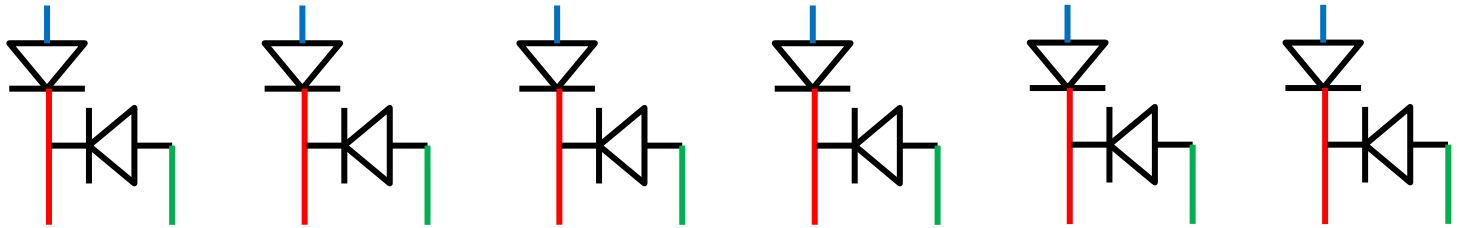




NOTE: Reverse connected configuration (r-type) of 3T cells with 2/1 voltages ratio for easy integration[1]

[1] H. Schulte-Huxel, et al., Progress in PV 31(12), 1350-1359, 2023

Interconnection of 3T cells



- First interconnection of IBC cells in series

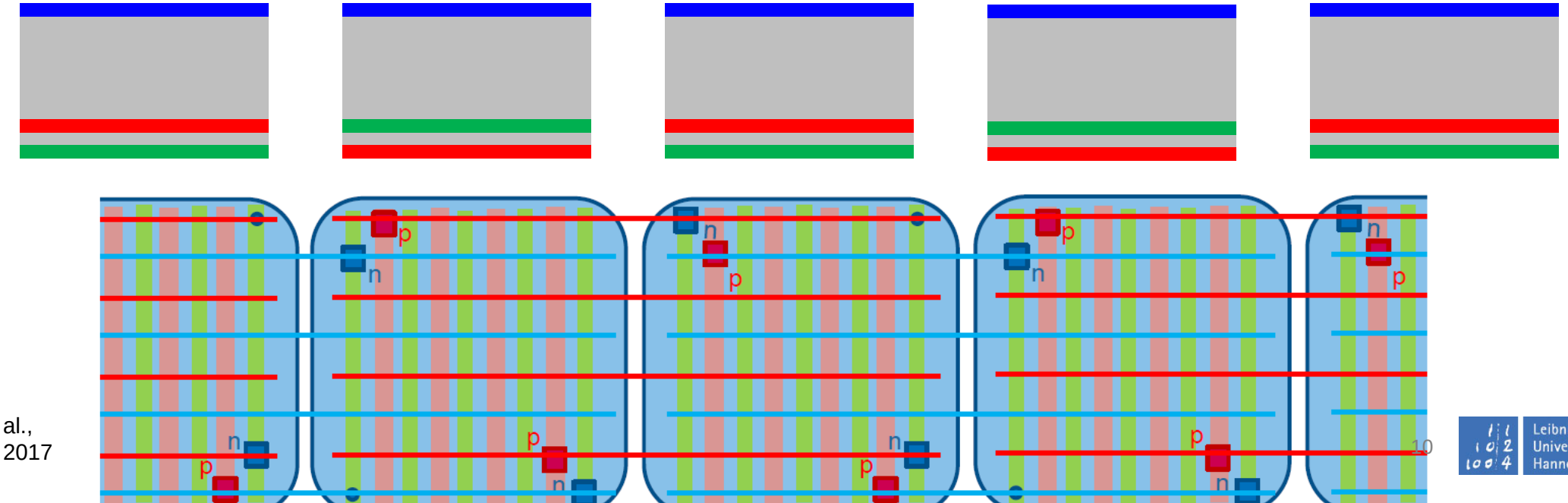


Image from: A. Faes et al., Metallization workshop 2017

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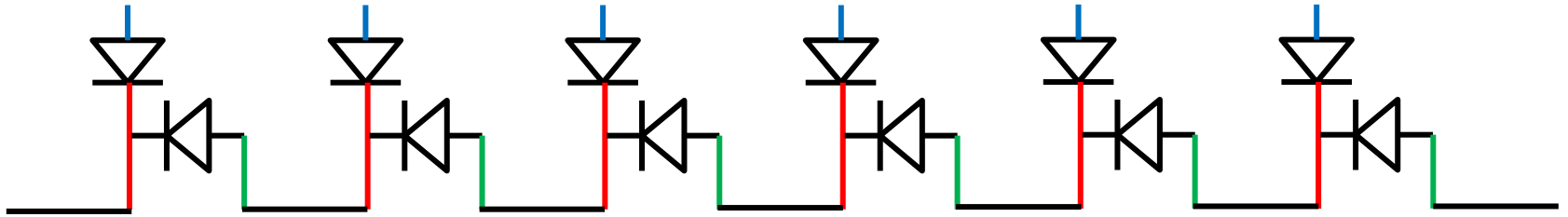

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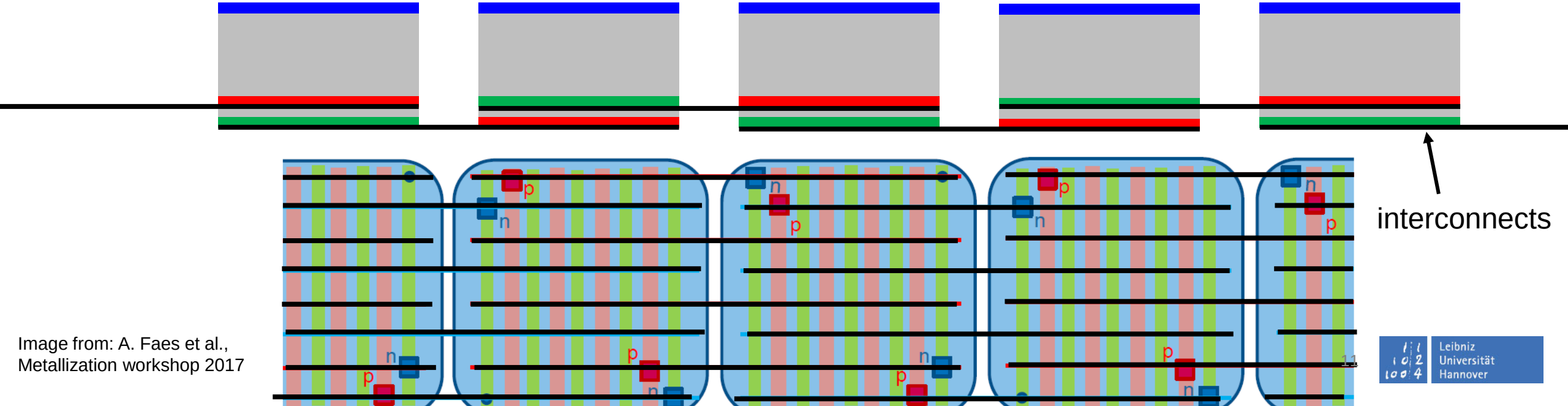

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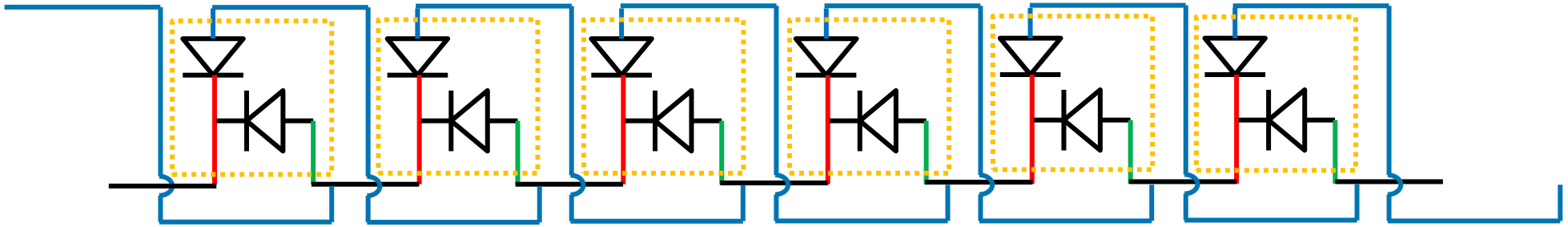
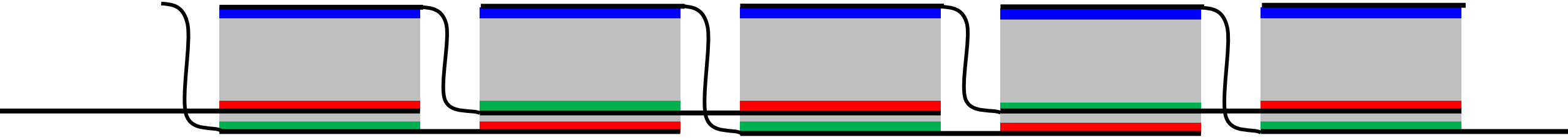
Leibniz Universität Hannover

Interconnection of 3T cells



- First interconnection of IBC cells in series
- Connecting front *p*-contact to back *n*-contact of next cell



- No crossing of wires (due horizontal displacement due to 180° rotation)

➔Simple combination of IBC and front back interconnection

➔Longer interconnects with corresponding series resistances[1,2]

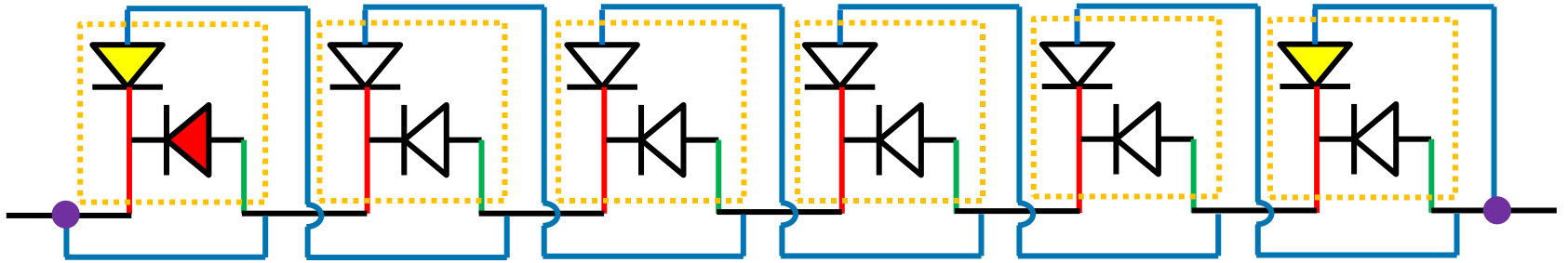
[1] H. Schulte-Huxel, et al., Progress in PV 31(12), 1350-1359, 2023
[2] M. Kikelj et al., Joule 8 1-20, 2024

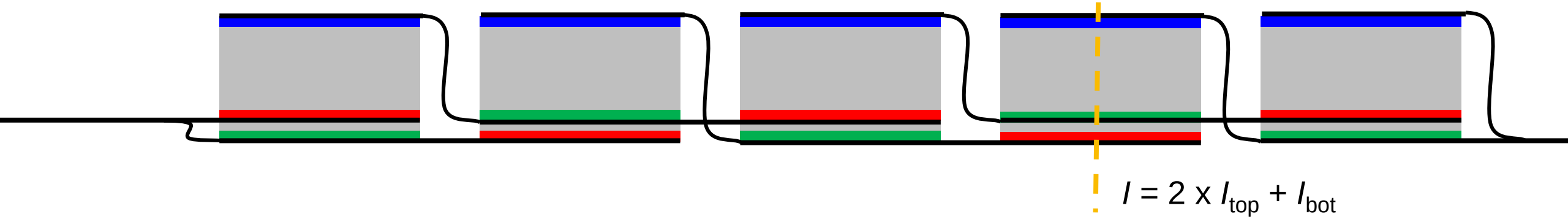
Interconnection of 3T cells

Cell operated at

½ voltage

0 voltage



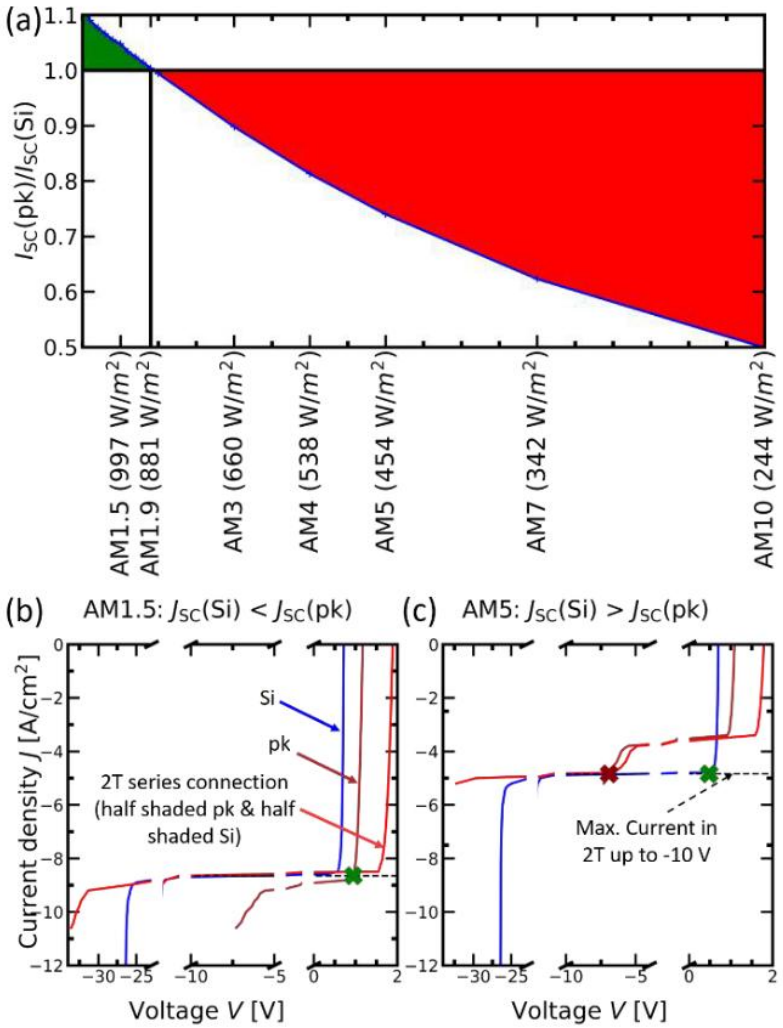


$I = 2 \times I_{top} + I_{bot}$

- Each cell is connected with the next and next-next cell
- To extract current, connectors need to be connected at the string ends leading to a string end loss of ~ the power of one cell[1]

[1] W. McMahon et al., IEEE J.PV 11 (4), 1078–1086, 2021.

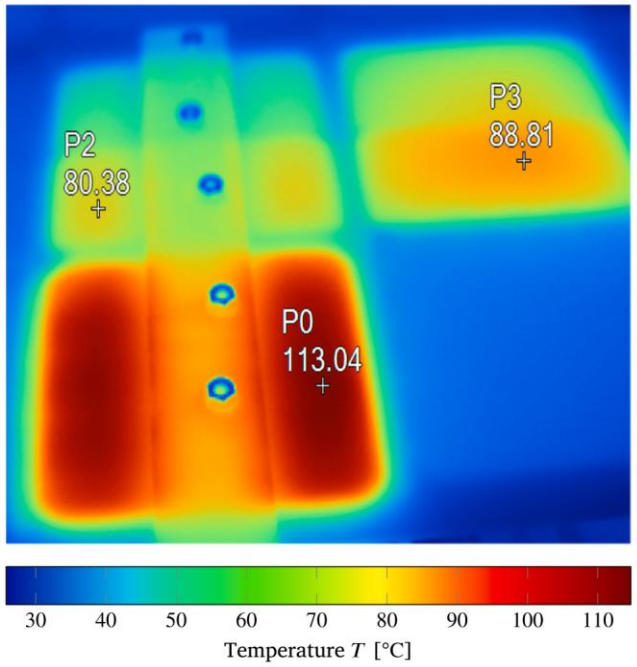
Partial shading and reverse voltage bias for 2T

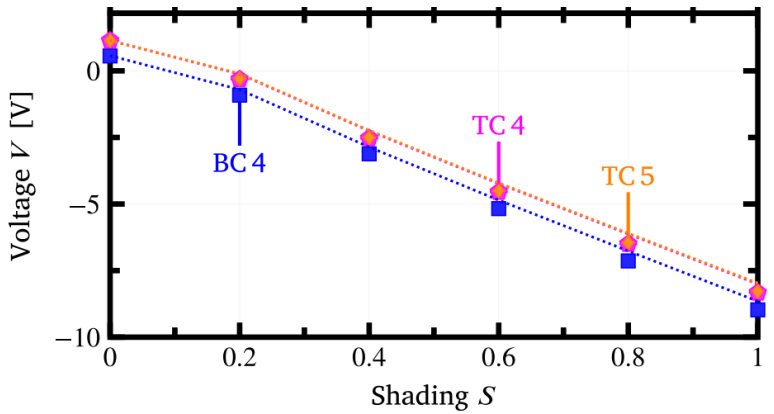


- Reverse voltage bias of top cell under partial shading is depending on daily changing spectrum
- for AM 1.5 to AM 1.9 (for mid summer day) Si bottom cell blocks current
  for AM >1.9 the perovskite solar cell blocks the current and gets into reverse bias
- ~8 V reverse bias voltage may apply for many hours per day if we use e.g. 6 cells per bypass diode

S. Baumann et al., Energy and Environmental Science 17, pp. 7566-7599, (2024)

Partial shading and reverse voltage bias for 3T



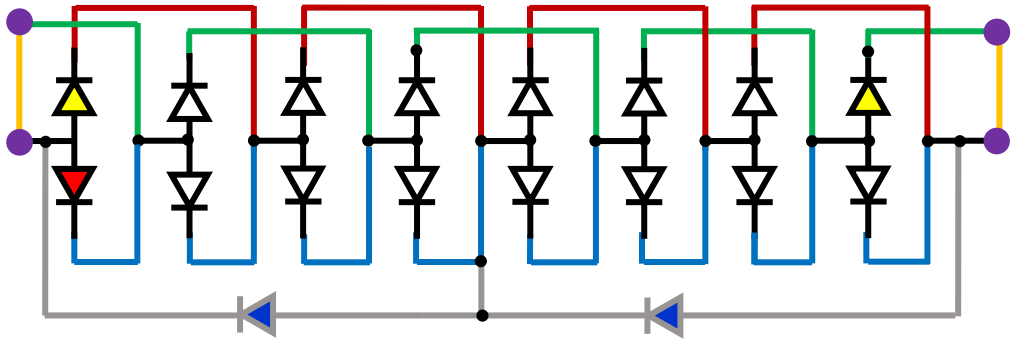


- 3T modules show advantages under partial shading[1]: three cells are reverse biased and share the dissipated power and split the required missing current
- Added voltage per cell in a string is the voltage of one bottom cell ~1/3 compared to 2T

➔ Multiple times longer strings protected by individual bypass diodes possible with 3T modules compared to 2T module

1 R. Witteck et al., Solar Energy Materials and Solar Cells, 219, 110811, 2021.

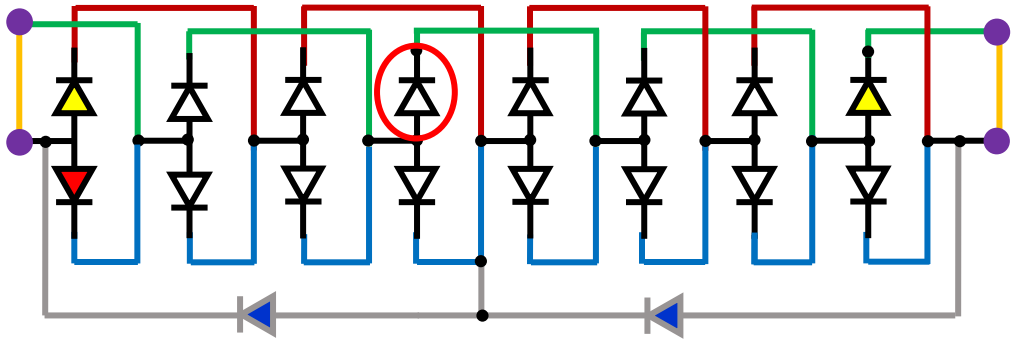
Bypass diode integration



- String ends need to be connected to one terminal
- But need bypass diodes for safe operation
  ➔ can we integrate bypass diodes without adding string end losses?

1 H. Schulte-Huxel, et al., Progress in PV 31(12), 1350-1359, 2023

Bypass diode integration



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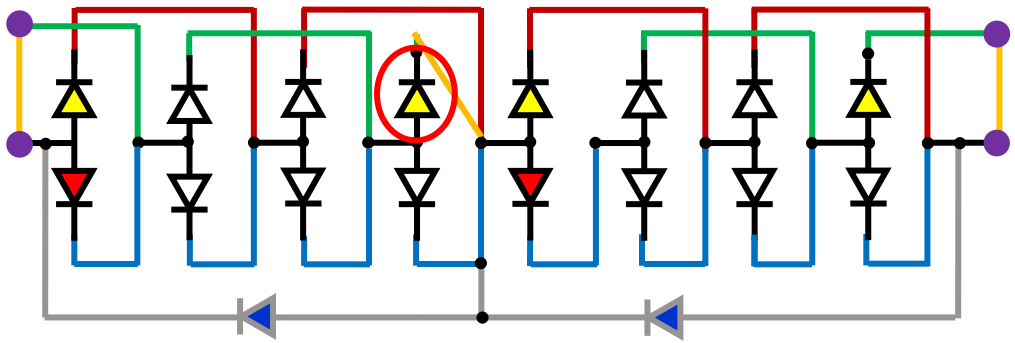

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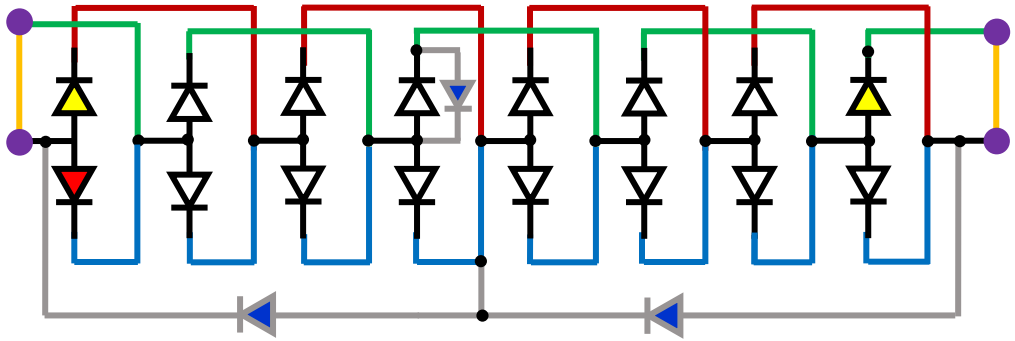

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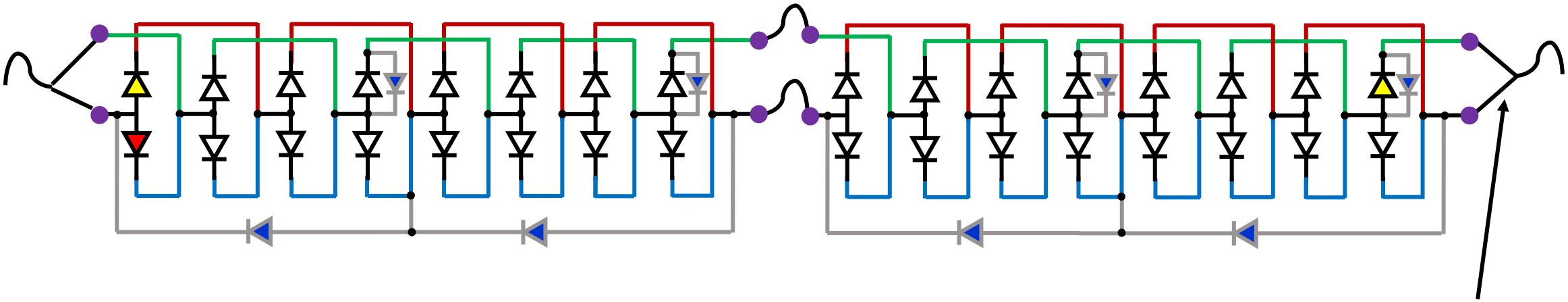
1 H. Schulte-Huxel, et al., Progress in PV 31(12), 1350-1359, 2023

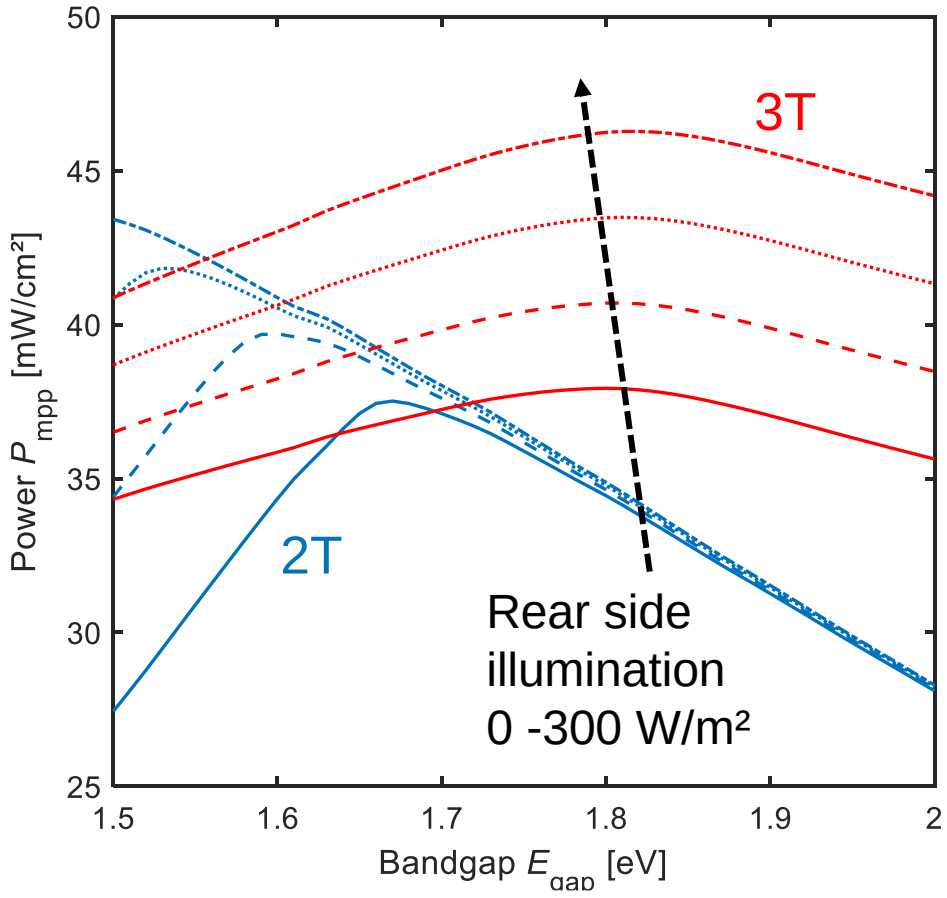
System integration concept



- String ends need to be connected to one terminal
- But need bypass diodes for safe operation
  ➔ can we integrate bypass diodes without adding string end losses?
- Yes, by an extra bypass diode to protect last top cell per string[1]
- Interconnect module with two cables per polarity
- Transfer of string end losses to end of module string on system level

1 H. Schulte-Huxel, et al., Progress in PV 31(12), 1350-1359, 2023

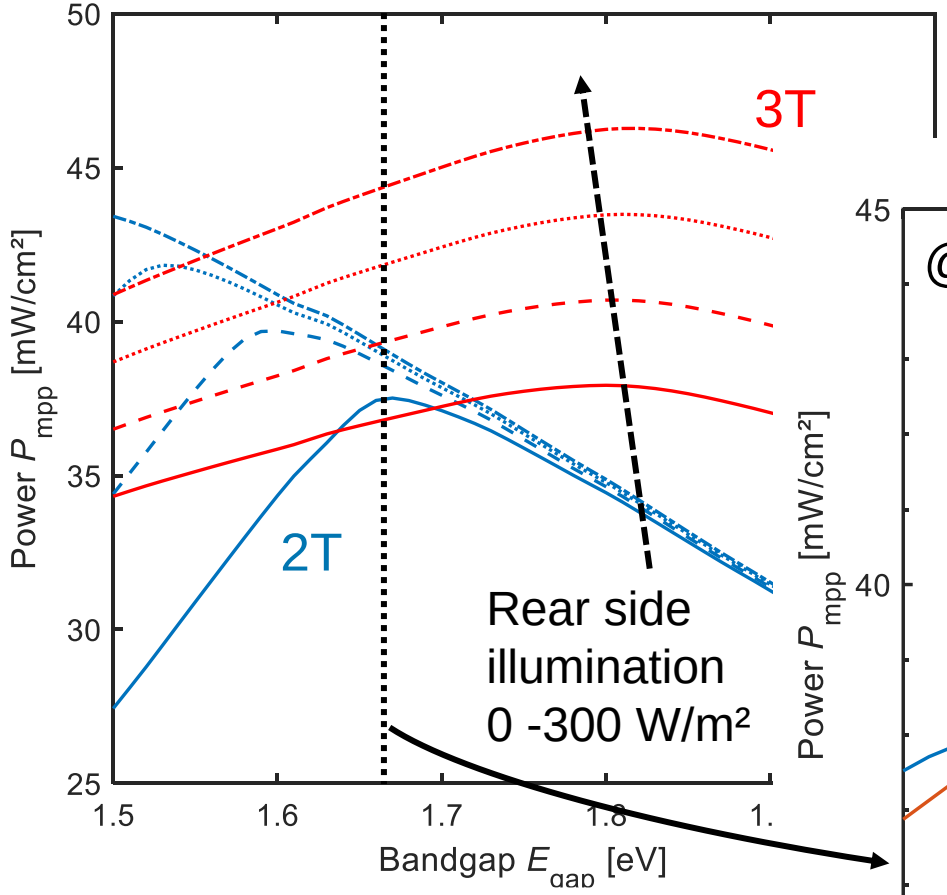
Bifacial behaviour

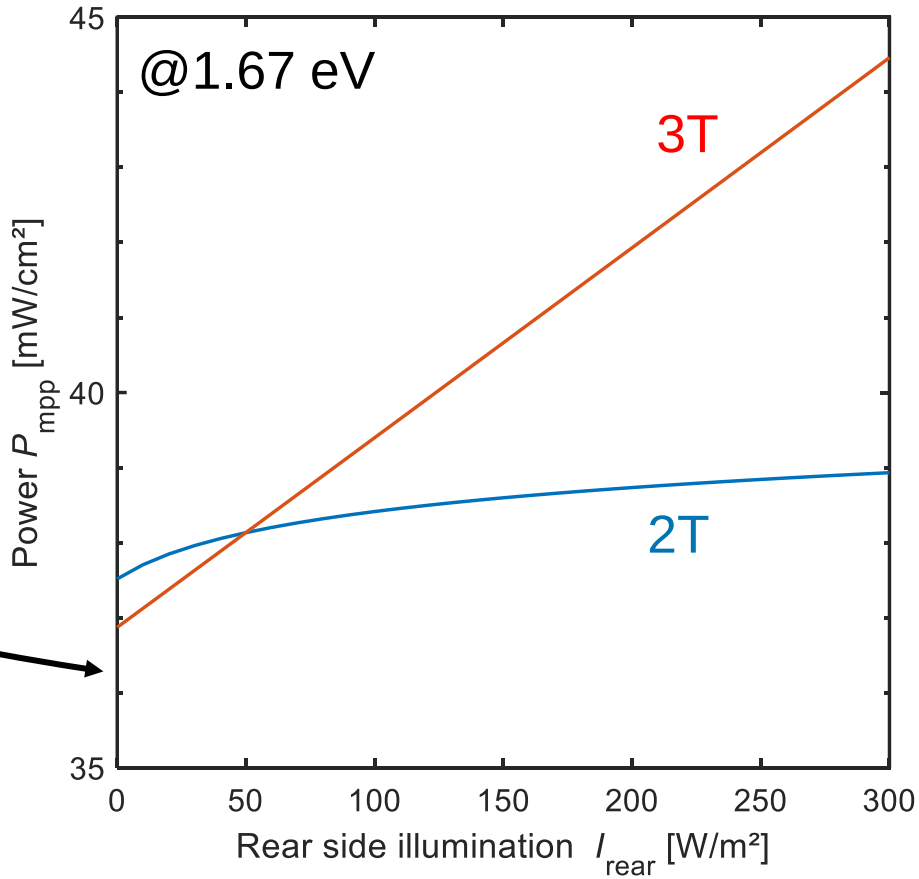


- 3T strings can fully harvest rear side illumination

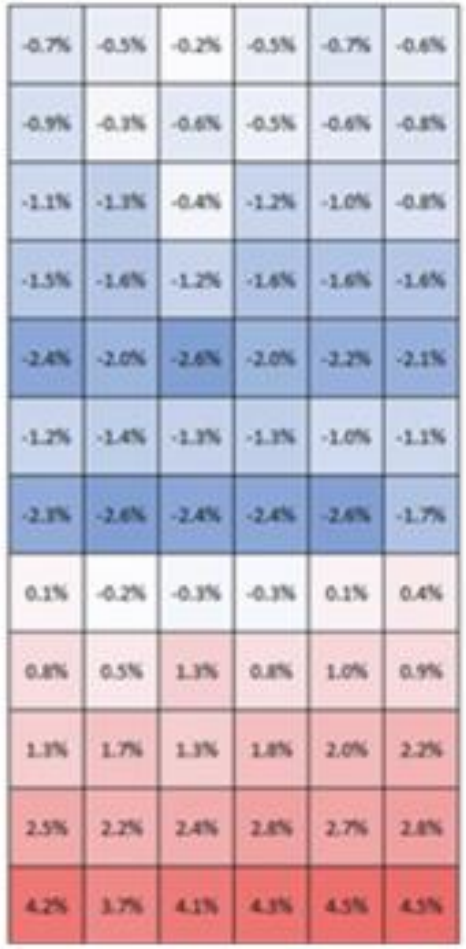
Bifacial behaviour

- 3T strings can fully harvest rear side illumination
- 2T devices mainly, when device is bottom cell limited and saturates fast for top cell limited operation





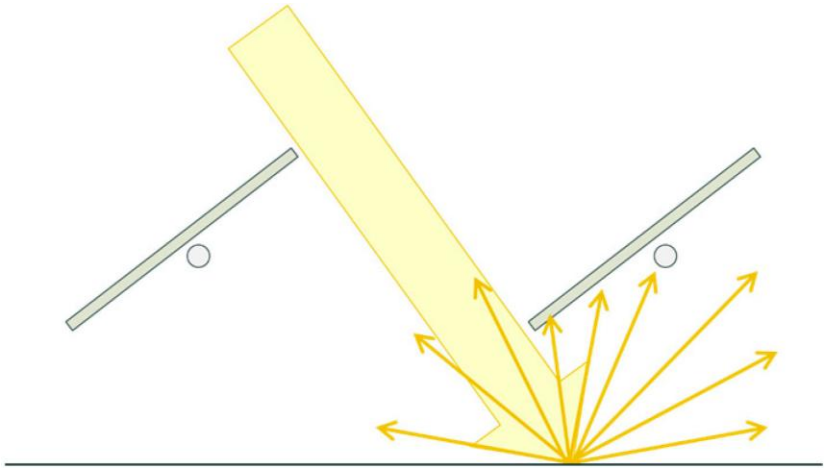
Bifacial operation of 2T tandem devices



Difference in current Δ*I*

-3.7% +4.5%

- Optimal current (and bandgap) ratio depends on installation condition
- Rear side irradiance is highly inhomogeneous due to e.g. distance to ground, ground shading, ground properties, supporting structure etc.
  and boosts only the current of bottom cell
  ➔ subcell mismatch leading to top cell limiting devices
- Challenge for current MPP tracking methods, as current in a string could be sufficient, but single cells already in critical reverse by inhomogeneous rear illumination or aging of top cells
- Bifacial module operation might be challenging for 2T Pk/Si tandem devices



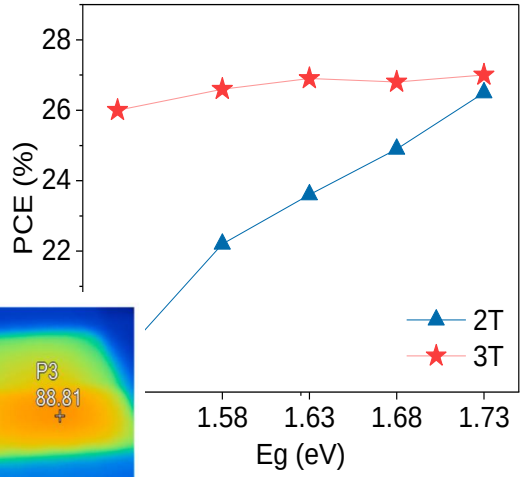
Images from:
K. R. McIntosh et al.,
IEEE Journal of Photovoltaics 9(6), 2019

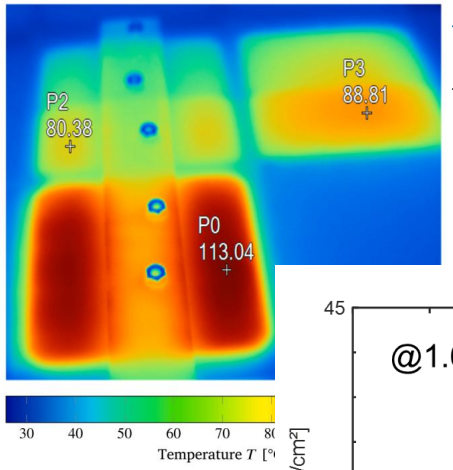
Leibniz Universität Hannover

Summary

- 3T specific cell-to-module losses are caused by:
  - Voltage matching with less yield losses than current matching
  - Longer interconnects with higher series resistance losses
  - String end losses

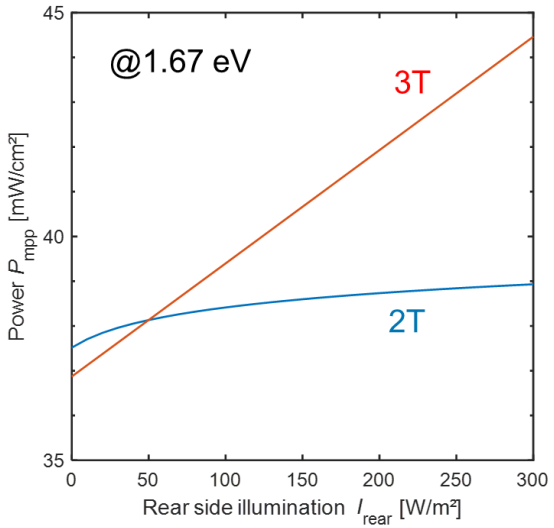
  ➔ can be transferred to end of module string on system level meanwhile protecting the string by bypass diodes





- But 3T devices show enhanced robustness against:
  - Spectral variations, but only small impact on energy yield
  - Non-perfect bandgap match

    ➔ Freedom of choice of top cell bandgap e.g. for higher stability
  - Change in current variation of subcells ➔ bifacial application
  - Partial shading



Acknowledgments

Thank you for your attention!

This work was funded by the state of Lower Saxony, by Deutsche Forschungsgemeinschaft (DFG) (Research Fellowship under grant agreement No: SCHU 3206/1-1) and the Federal Ministry for Federal Minister for Economic Affairs and Energy (BMWE) under grant number 03EE1056A (27plus6).

Supported by:

Federal Ministry for Economic Affairs and Energy

by the German Bundestag