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Influence of the Transition Region Between *n*- and *p*-Doped Silicon on IBC Solar Cells

Jonas D. Huyeng, Christian Reichel, Ralph Müller, Andreas Fell, Roman Keding, Florian Clement, Martin Hermle, Stefan W. Glunz

10th BCworkshop, 21.11.2022, Konstanz

Solar Cell Research at Fraunhofer ISE

Research for the Energy Transition (over 40 years)

BCworkshop since 2009

- 1st Workshop on MWT technology, 2009, Freiburg (w/ ECN)

Applied Research on Solar Technology

- Business Area Photovoltaics: ca. 700 employees (incl. students)
- CalLab PV Cells – Calibrated Measurements

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CalLab PV Cells

Measurement of Back Contact Cells

CalLab PV Cells
cells@callab.de

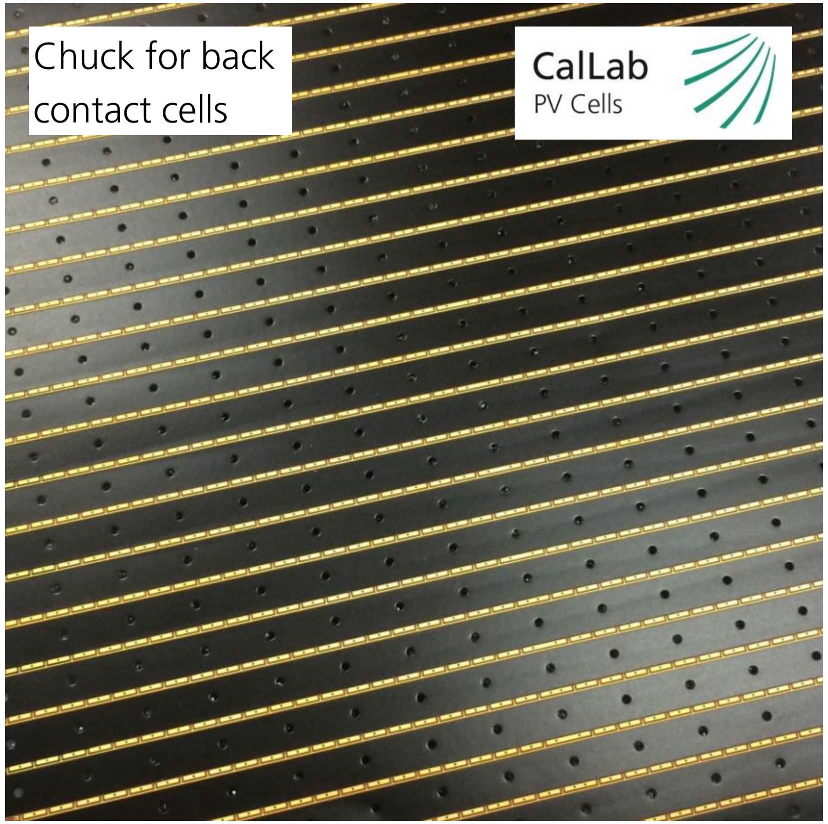
Compatible with cell formats up to M12

No front glass

- Electrical and thermal contact by vacuum suction
- Tactile measurement of solar cell temperature possible
- Irradiance not affected

Separate current and voltage contacts

- Very narrow contact structures feasible (minimum structure size of ca. 500 µm)
- Busbar and point-like contact structure



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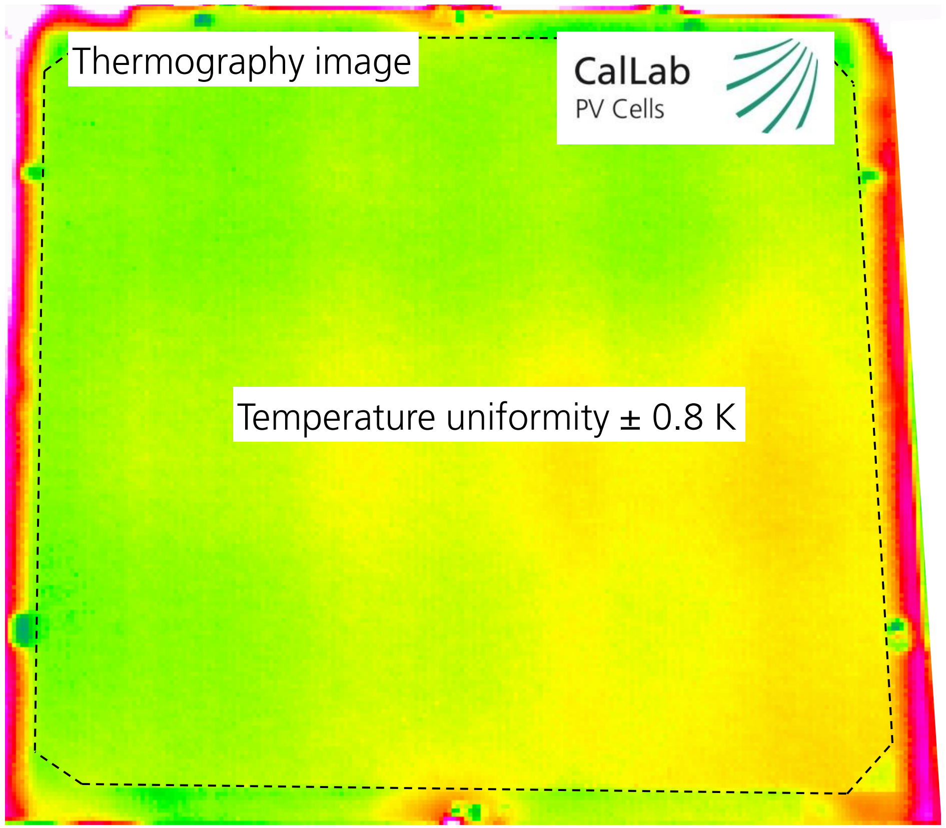
High temperature uniformity

- Temperature variation ± 0.8 K
- Measurement of temperature coefficients



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- Temperature variation ± 0.8 K
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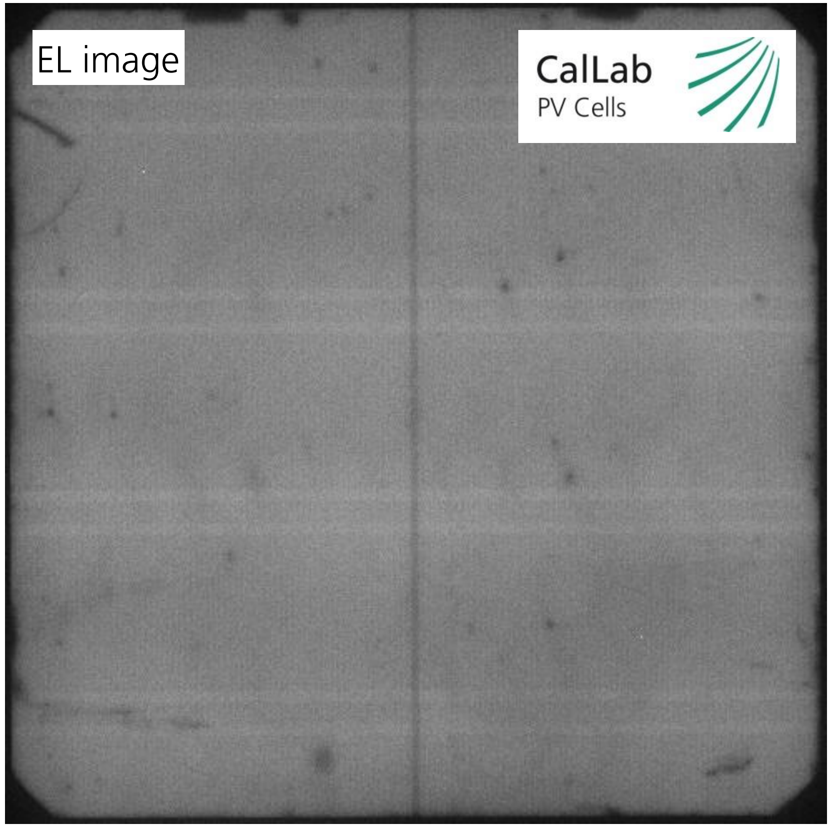
High potential uniformity



➔ Simple and cost-effective customization for customers

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- CalLab PV Cells – Calibrated Measurements
- Center for Highest Efficiency Solar Cells (ZhS - 2021)
- Photovoltaic Technology Evaluation Center (PV-TEC)
  - Front-End: 1000 m²
  - Back-End: 1230 m²

Industrial Silicon Solar Cells on Pilot Lines

- Passivated Emitter and Rear Cells (PERC)
- Tunnel-oxide Passivated Contact Cells (TOPCon)
- Silicon Heterojunction Cells (SHJ)

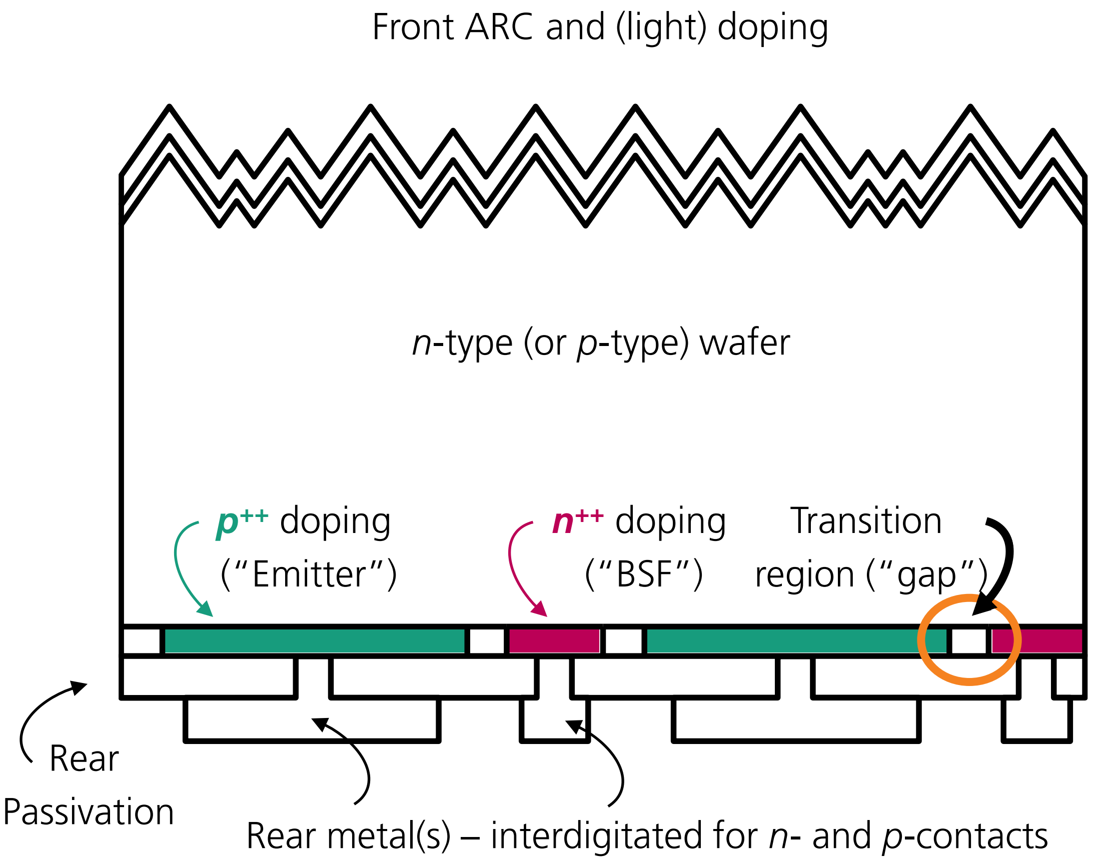
- Interdigitated Back-Contact Cells (IBC)*
  - Metal-Wrap Through (MWT)
  - **Back-Contact Back-Junction (BCBJ)**

* J. D. Huyeng *et al.*, 9th BCworkshop: https://www.backcontact-workshop.com/pdf/2022-1/4_ISE.pdf

Interdigitated Back-Contact Solar Cells

Back-Contact Back-Junction Architecture

Schematic

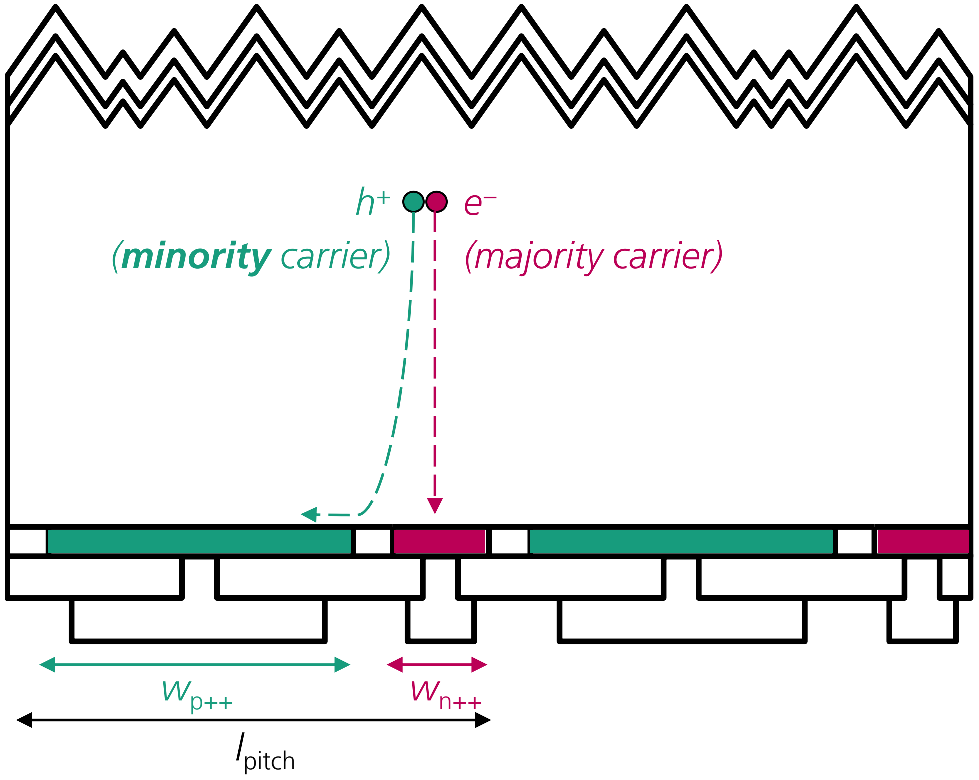


ARC = Anti-reflection coating
BSF = Back-surface field

Current Collection in IBC Solar Cells

Lateral Transport of (Minority) Charge Carriers

Schematic (*n*-type IBC)



Current Collection in IBC Solar Cells

Lateral Transport of (Minority) Charge Carriers

Schematic (*n*-type IBC)

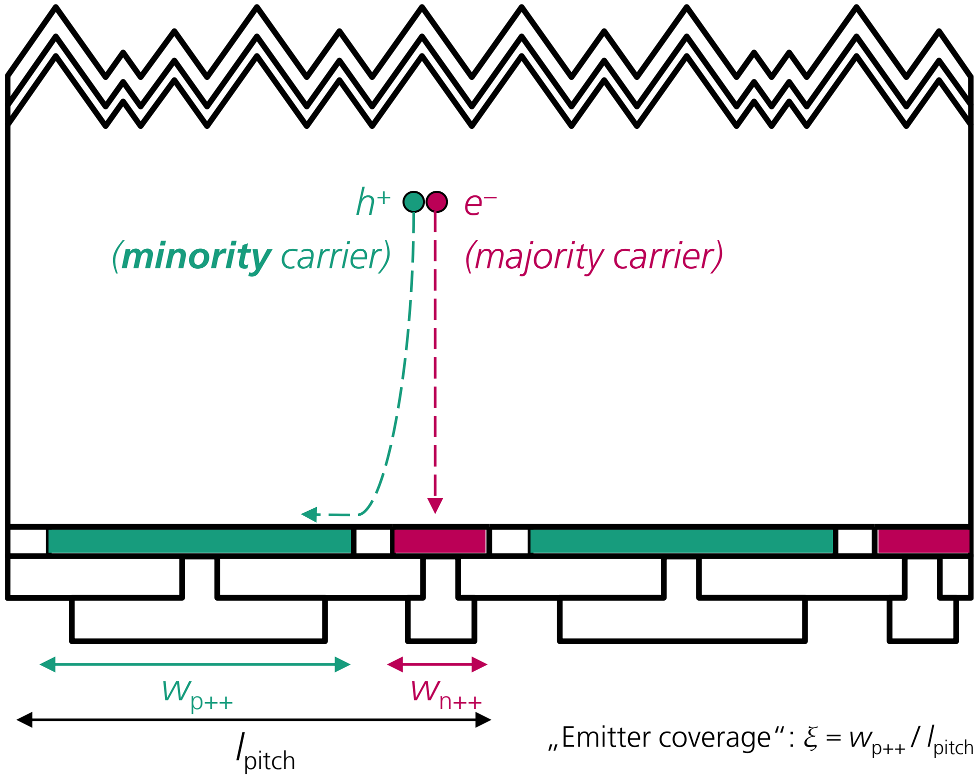
Typical dimensions

- Wafer thickness t ~ 160 µm
- BSF widths w_{n++} ~ 300 µm
- Gap widths w_{gap} ~ 150 µm
- Emitter widths w_{p++} ~ 1600 µm

Maximizing the Emitter Coverage

The Buried Emitter and Floating Base Concepts

Schematic (*n*-type IBC)

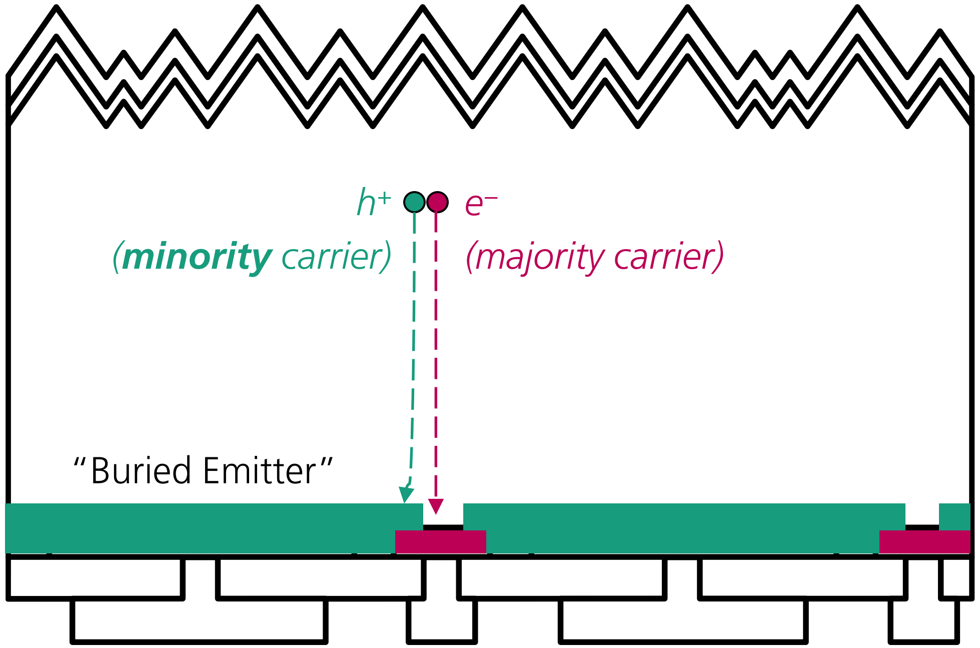


„Emitter coverage": $\xi = w_{p++} / l_{pitch}$

Maximizing the Emitter Coverage

The Buried Emitter and Floating Base Concepts

Schematic (*n*-type IBC)



[1] Harder, N.-P.; Mertens, V.; Brendel, R. (2008), *Phys. Status Solidi RRL* 2 (4), S. 148–150. DOI: 10.1002/pssr.200802113.

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The Buried Emitter and Floating Base Concepts

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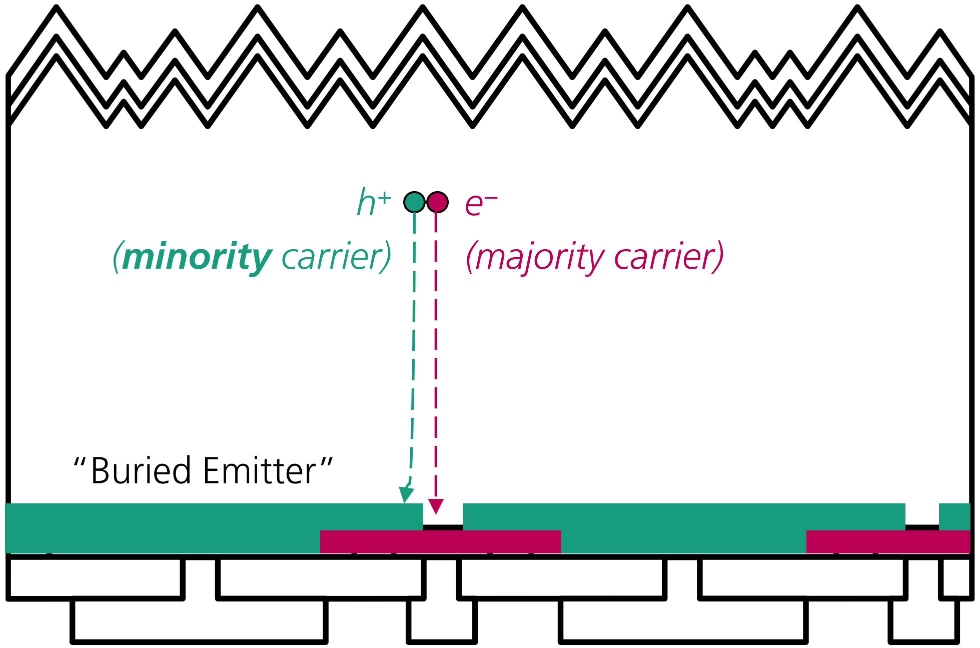

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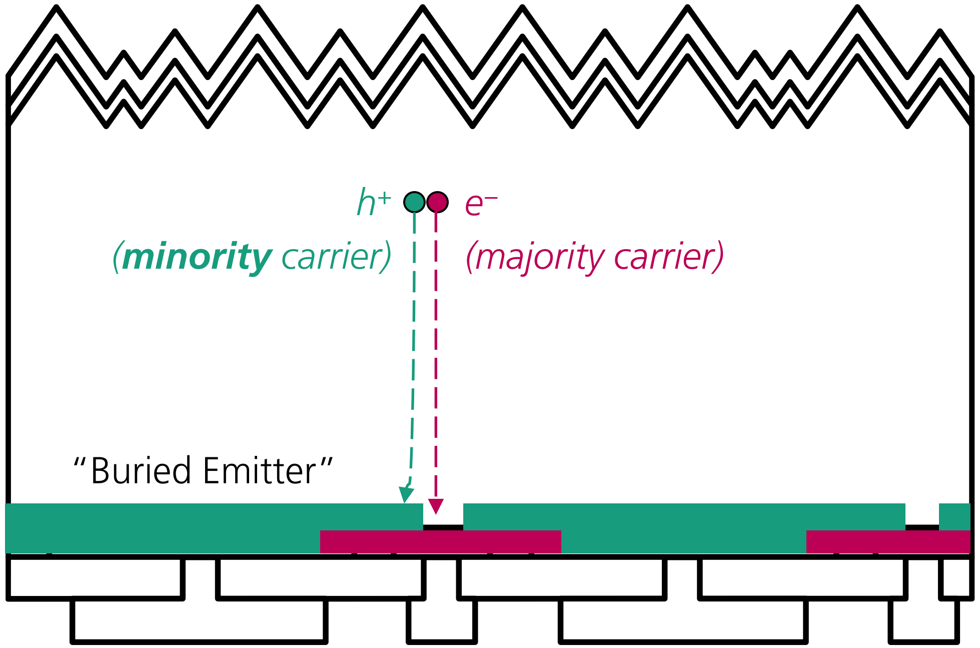

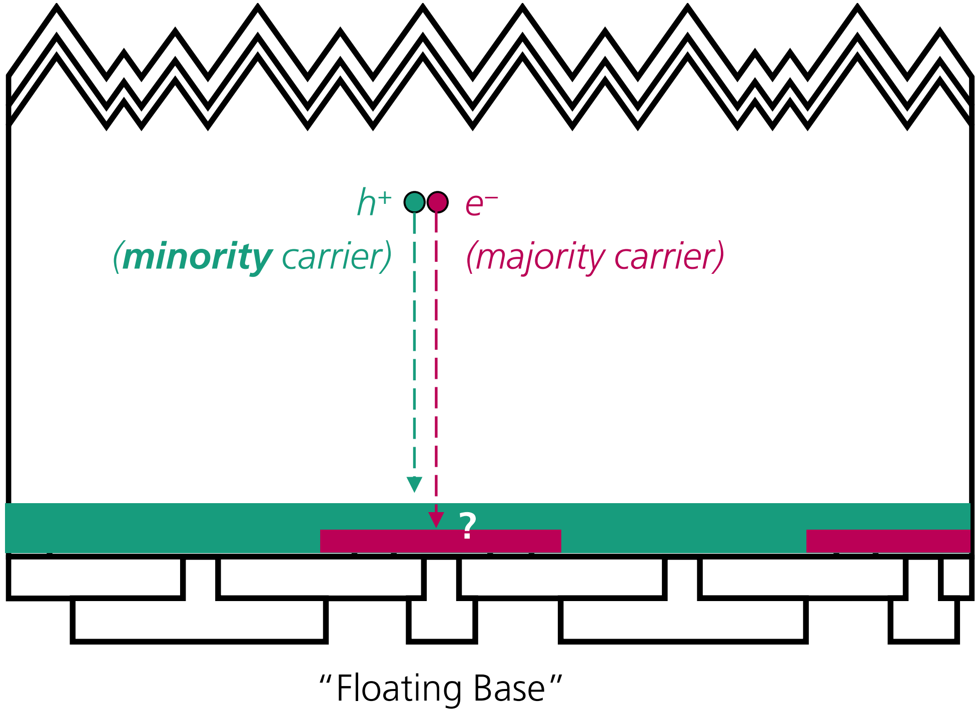

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[2] Reichel, C.; Fell, A.; Hermle, M.; Glunz, S. W. (2019): *Phys. Status Solidi* A 216 (4), S. 1800791. DOI: 10.1002/pssa.201800791.

Maximizing the Emitter Coverage

Fabrication of Buried Emitters and Floating Base

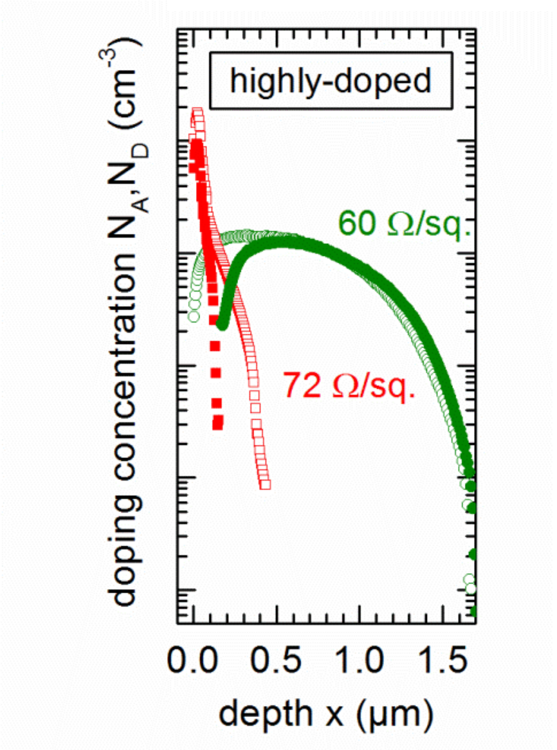
Process technology

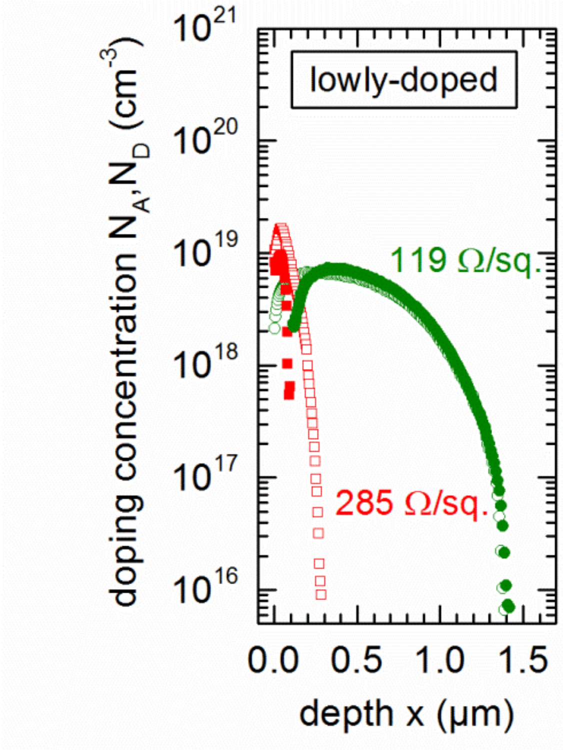
- (Masked) diffusion of B Emitter doping
  - Deep diffusions (green)
- Masked diffusions of P BSF doping
  - Shallow diffusion (red)
  - Overcompensation of B near surface (filled)

- Full contact of B and P diffusion
  - Additional vertical junction (n^{++}-p^{++}-n, s. right)
  - Lateral “high-high” junction

Experimental approach[2]

- Pitch distance: l_{pitch} = 1100 µm
- Reference (gaps): w_{p++} = 800 µm, w_{n++} = 150 µm
- Buried Emitter: w_{p++} = 1050 µm, w_{n++} = 550 µm
- Floating Base: w_{p++} = 1100 µm, w_{n++} = 550 µm





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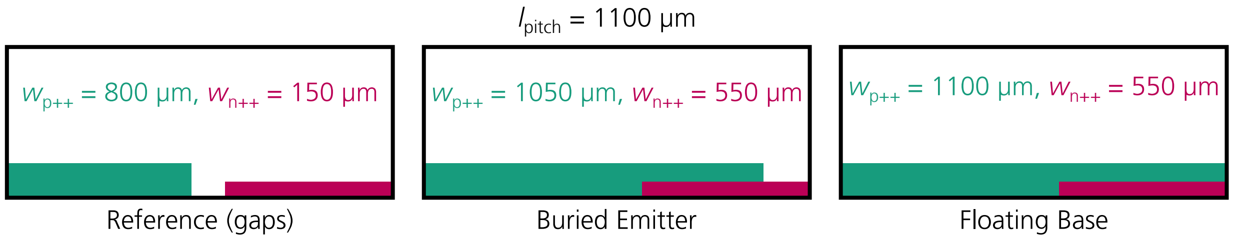
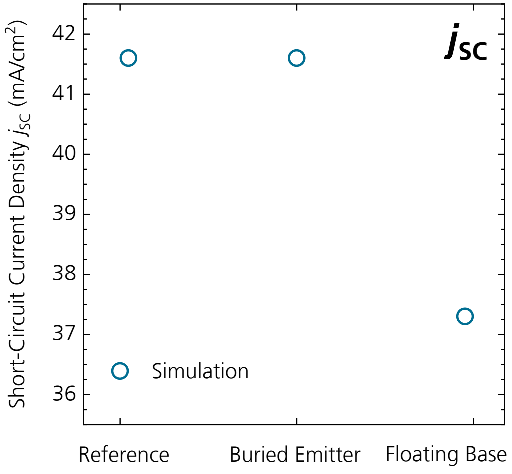
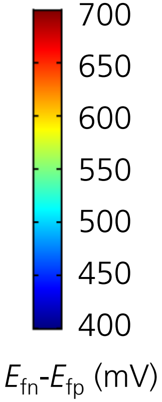
Maximizing the Emitter Coverage

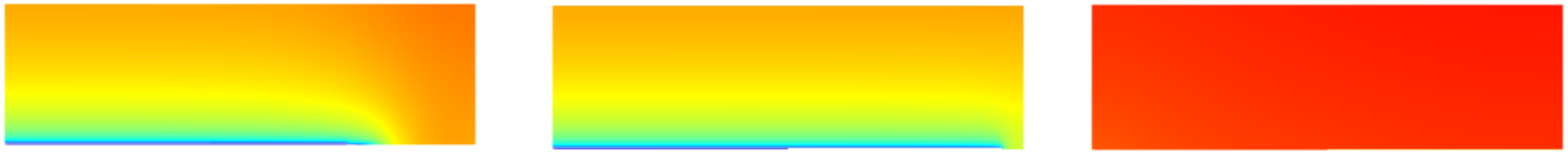
Buried Emitters in the Transition Region





Simulation (short-circuit)



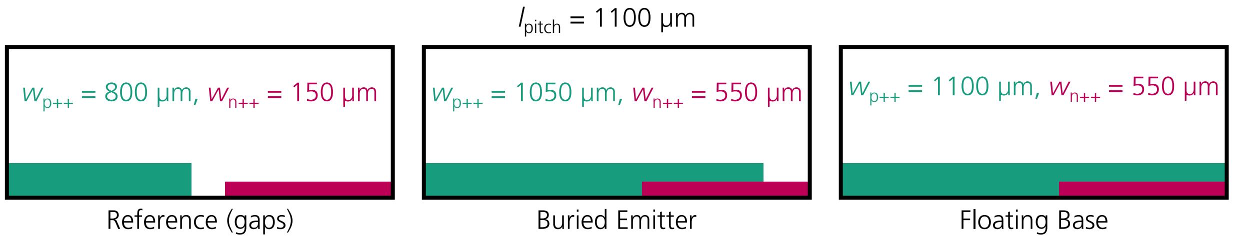


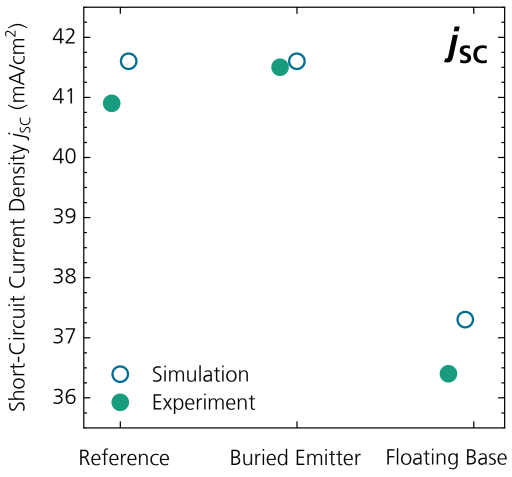
Reference (gaps) | Buried Emitter | Floating Base

[2] Reichel, C.; Fell, A.; Hermle, M.; Glunz, S. W. (2019): *Phys. Status Solidi* A 216 (4), S. 1800791. DOI: 10.1002/pssa.201800791.

Maximizing the Emitter Coverage

Buried Emitters in the Transition Region





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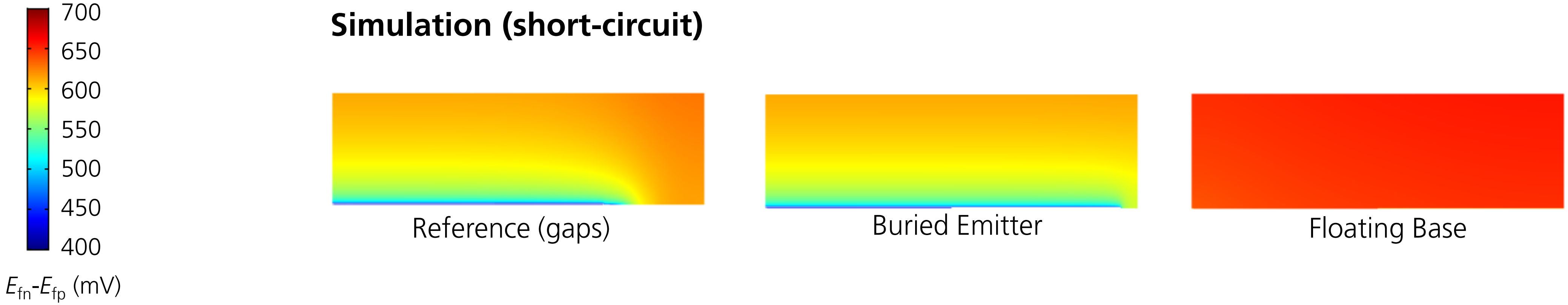

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Maximizing the Emitter Coverage

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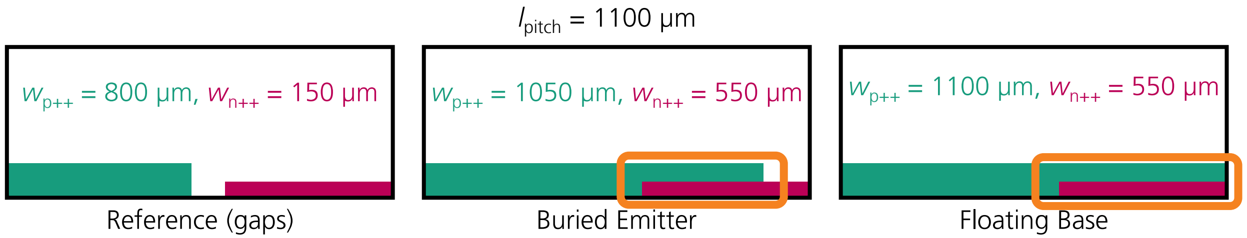
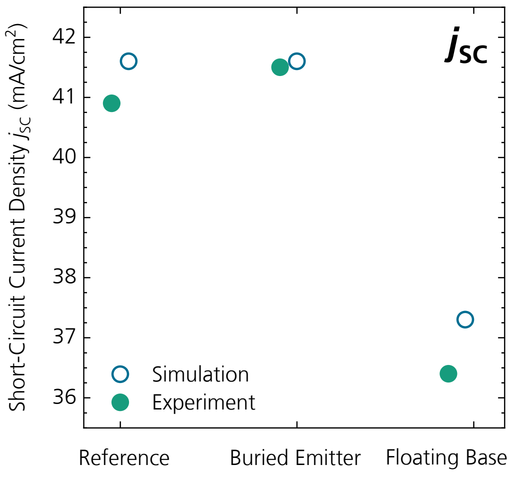
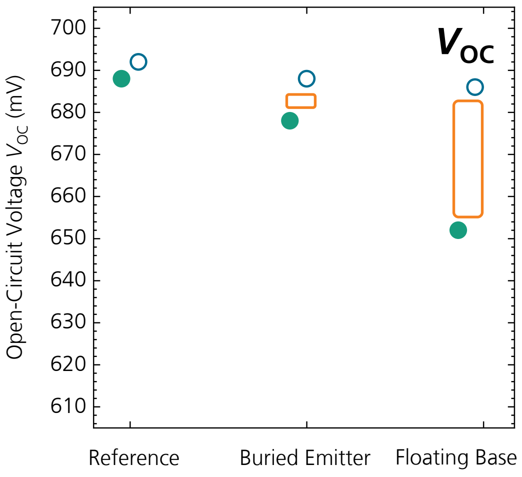
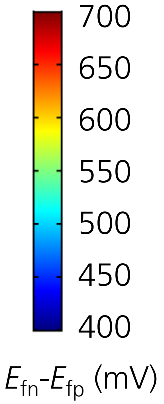






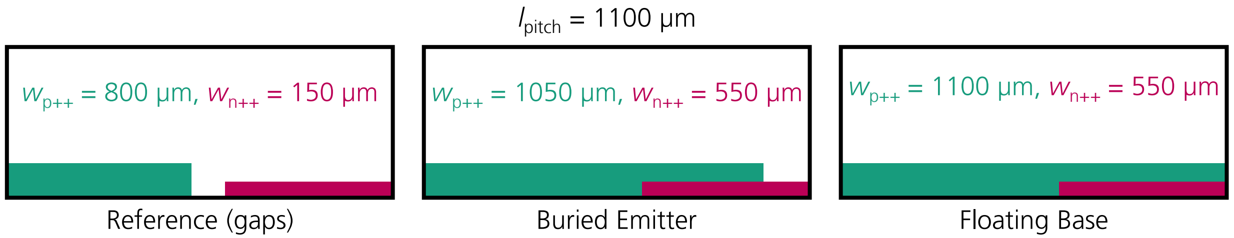


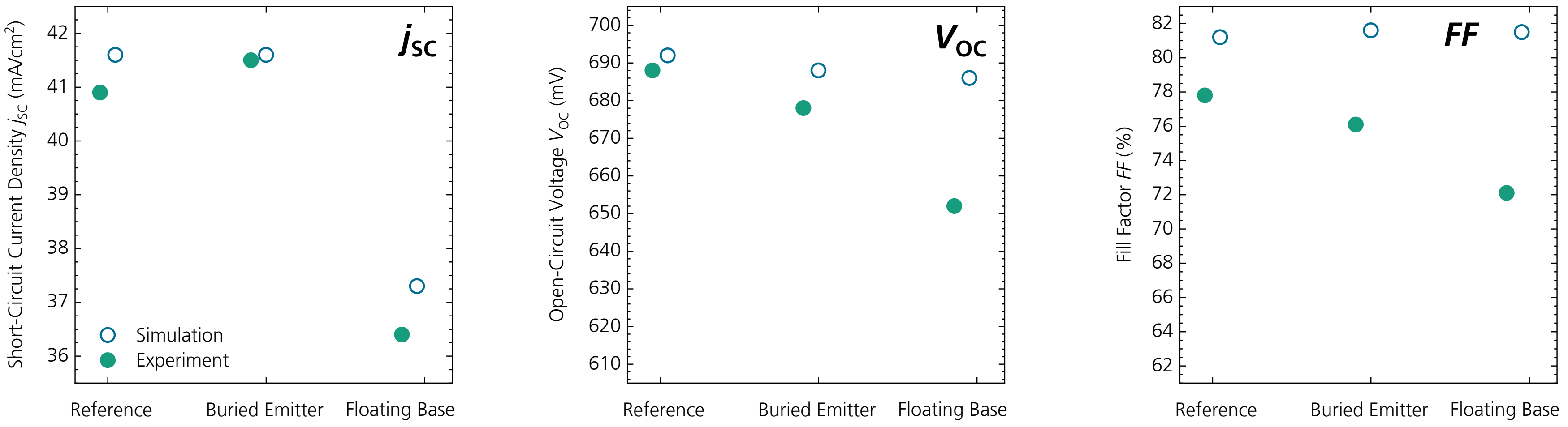
Simulation (open-circuit)

[2] Reichel, C.; Fell, A.; Hermle, M.; Glunz, S. W. (2019): *Phys. Status Solidi* A 216 (4), S. 1800791. DOI: 10.1002/pssa.201800791.

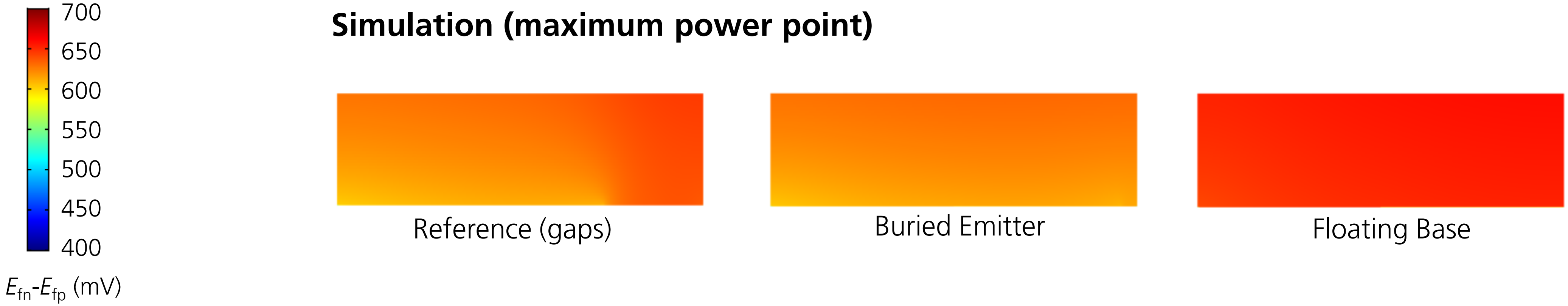
Maximizing the Emitter Coverage

Buried Emitters in the Transition Region





Simulation (maximum power point)



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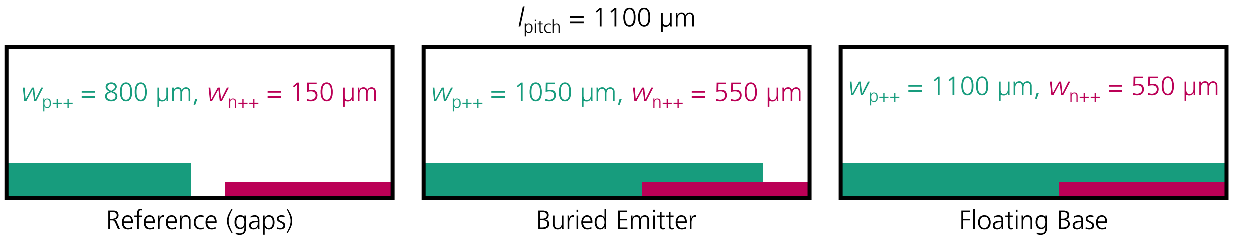
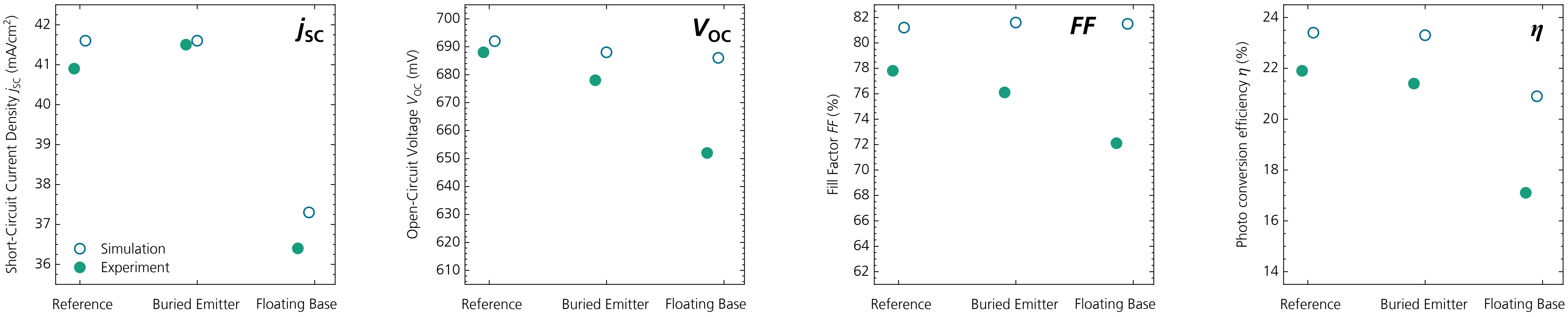
Buried Emitters in the Transition Region





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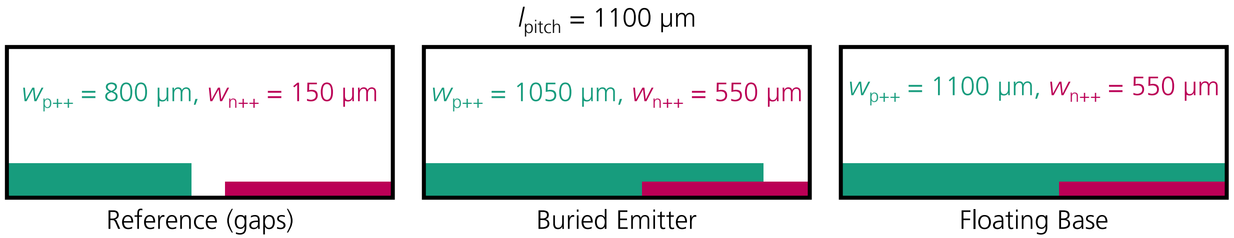

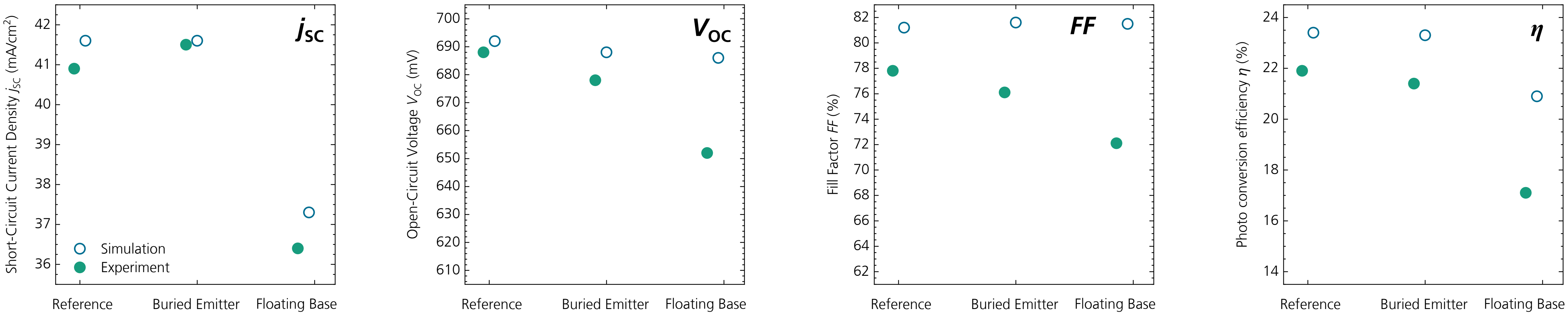

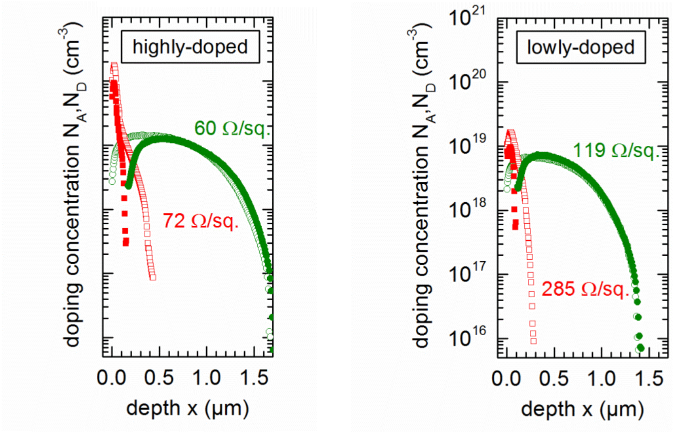

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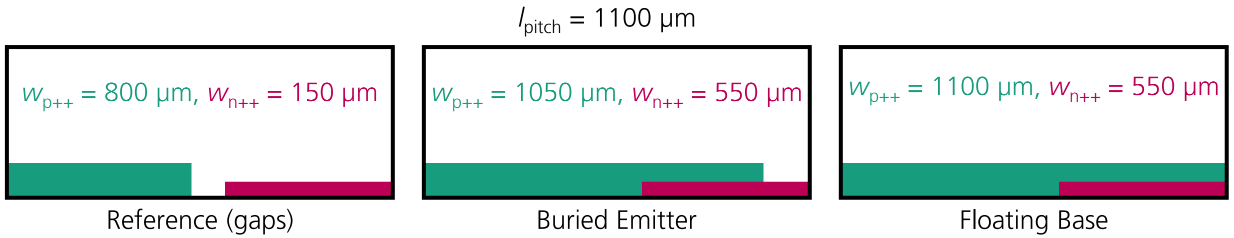

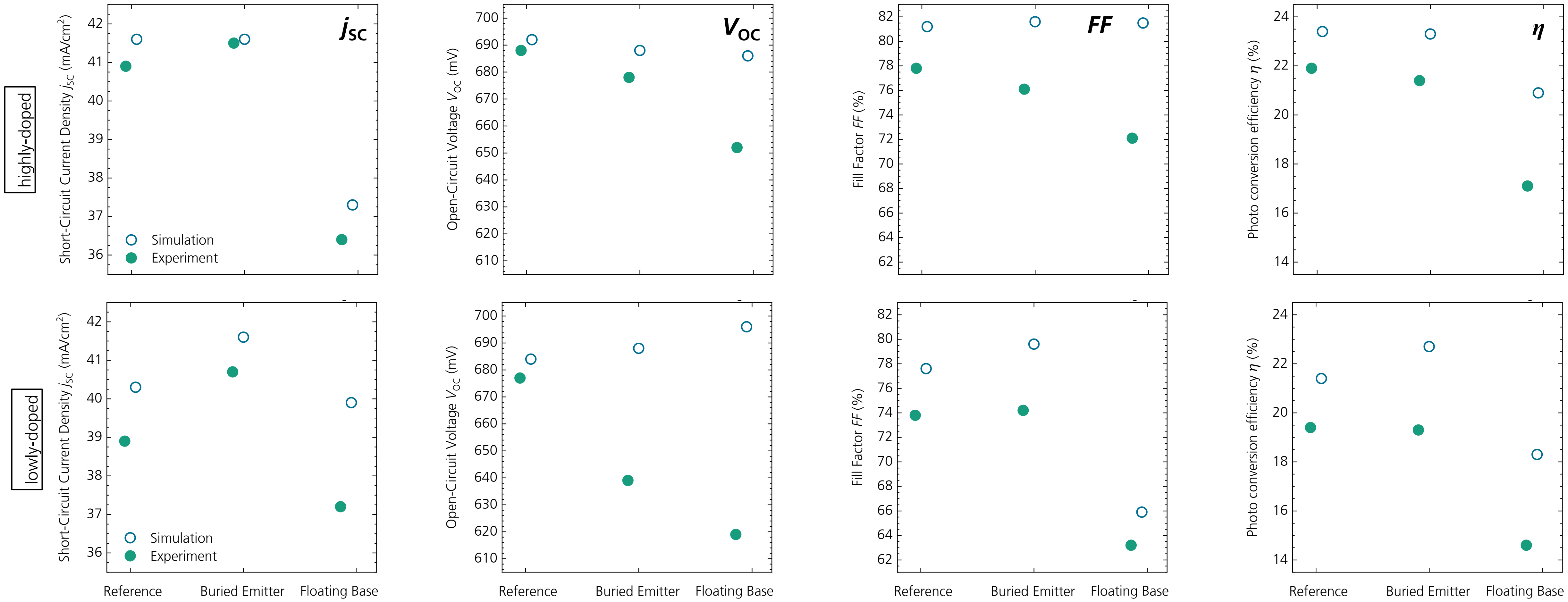

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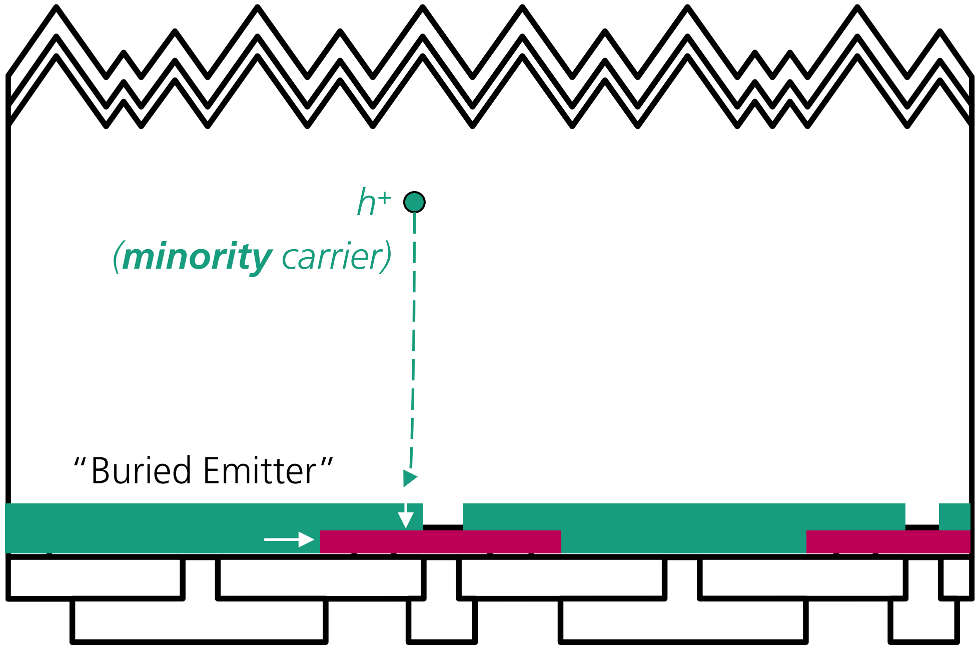
Maximizing the Emitter Coverage

Buried Emitters in the Transition Region

Recombination in IBC solar cells

- Bulk recombination (intrinsic)
- Surface recombination
- Non-ideal recombination (junctions)
  - Vertical* and lateral junction contacts (transition region)

Schematic (*n*-type IBC)



* More possibly later today …

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Maximizing the Emitter Coverage

~~Buried Emitters in the Transition Region~~ Gapless Cells

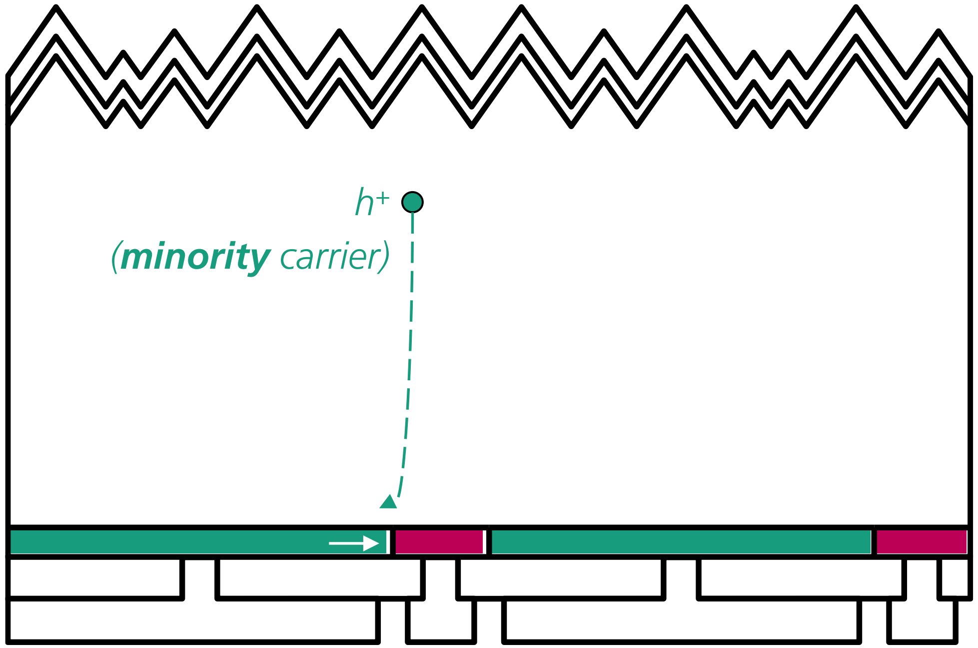
Recombination in IBC solar cells

- Bulk recombination (intrinsic)
- Surface recombination
- Non-ideal recombination (junctions)
  - Vertical* and lateral junction contacts (transition region)

“Gapless” IBC solar cells

- Only lateral junction contact
  - If solar cell is truly gapless, *i.e.*, without etched steps
- More simple fabrication

Schematic (*n*-type IBC)



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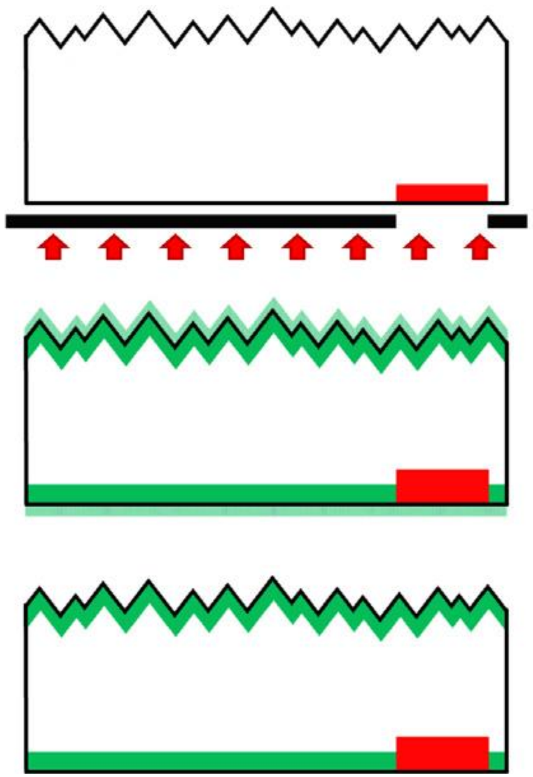
Eliminating the Transition Region

Gapless IBC Solar Cells

Simplified IBC Process Sequence

Reference (Gaps)	*"P-Blocking"*[1]	*"Co-Diffusion"*[2]
Cleaning, Texturing, …		
Mask for p^{++}	(Mask for n^{++})	Print multifunction B layer
B diffusion	(Masked) P implantation	P diffusion
Mask removal	(Mask removal)	FS Etch Back
Mask for n^{++}	B diffusion	
Mask removal		
P diffusion		
Mask for n^{+} (FS)		
P diffusion		
Mask removal		
Cleaning, Passivation, Metallization, …		

P-Blocking by Ion Implantation



Masked P Ion Implantation
(n^{++} Definition)

BBr3 Furnace Diffusion
(p^{++} front and rear)
⇒ Local Blocking by P

Cleaning
⇒ Truly "gapless"

[1] Müller, R.; Reichel, C.; Schrof, J.; Padilla, M.; *et al.* (2015): *Sol. Energy Mater. Sol. Cells* 142, S. 54–59. DOI: 10.1016/j.solmat.2015.05.046.
[2] Huyeng, J. D.; Efinger, R.; Keding, R. J.; Doll, O.; Clement, F. (2020): *Sol. RRL* 4 (10), S. 2000271. DOI: 10.1002/solr.202000271.

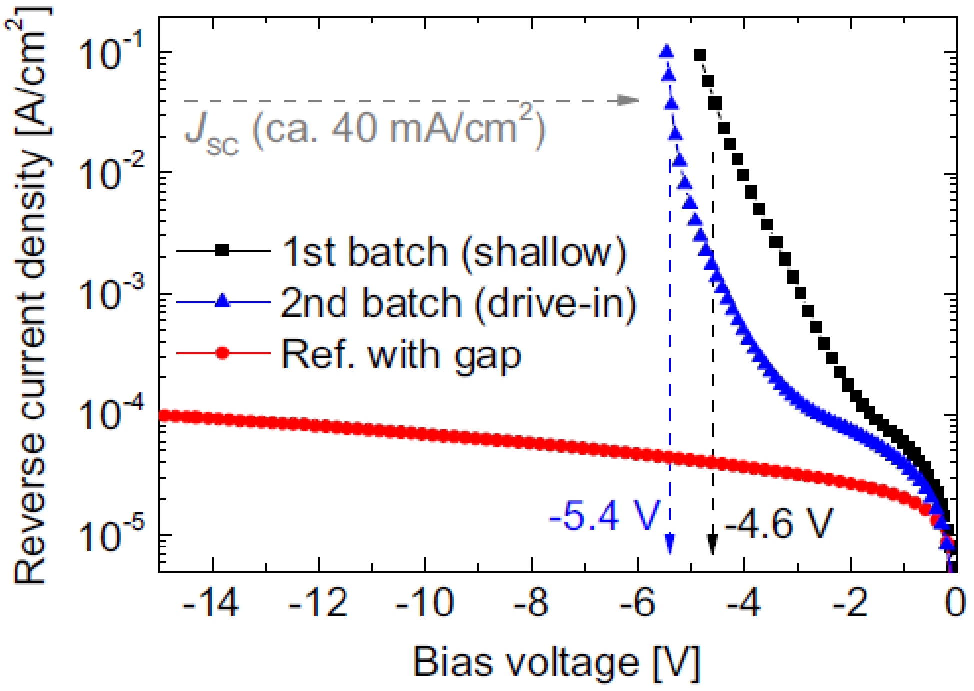
Eliminating the Transition Region

Simplified IBC sequence by P-Blocking

“Gapless” IBC solar cells

- Simple process sequence, *e.g.,* by P-Blocking
- Lateral recombination noticeable in reverse bias[1]
  - Soft breakdown due to lateral junction (“high-high”)
  - May influence charged dielectric (*e.g.,* Al_2O_3)[2]

- BSF widths limits emitter coverage
  - “Electrical shading” due to h^+ loss



[1] Müller, R.; Reichel, C.; Schrof, J.; Padilla, M.; *et al.* (2015): *Sol. Energy Mater. Sol. Cells* 142, S. 54–59. DOI: 10.1016/j.solmat.2015.05.046.
[2] Müller, R.; Reichel, C.; Yang, X.; Richter, A.; Benick, J.; Hermle, M. (2017): *Energy Proced.* 124, S. 365–370. DOI: 10.1016/j.egypro.2017.09.311.

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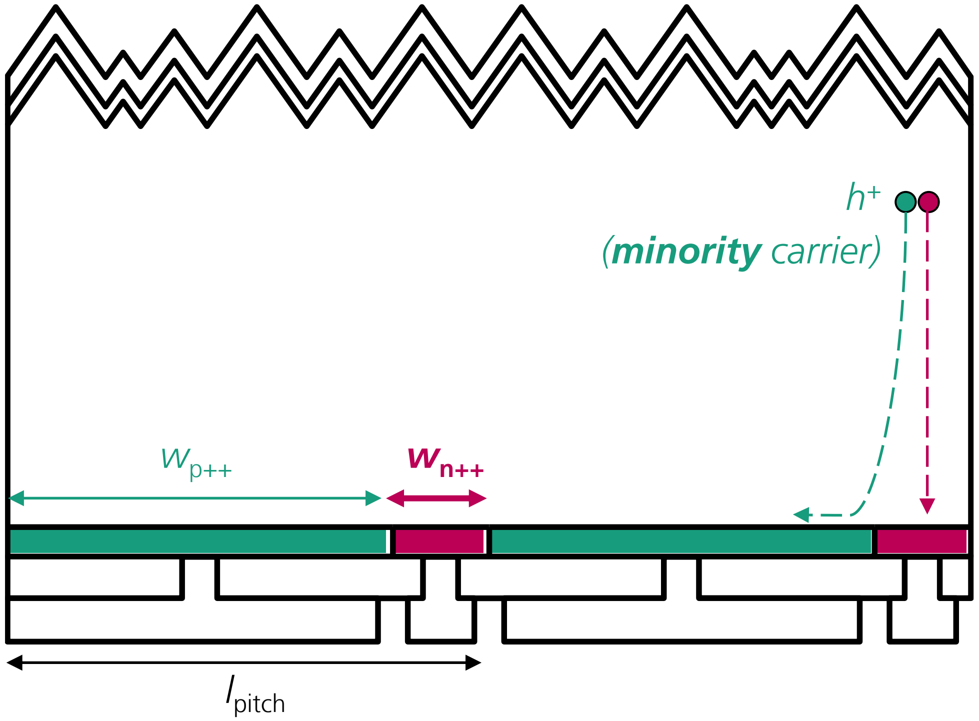
Eliminating the Transition Region

Occurrence of “Electrical shading” in IBC Solar Cells

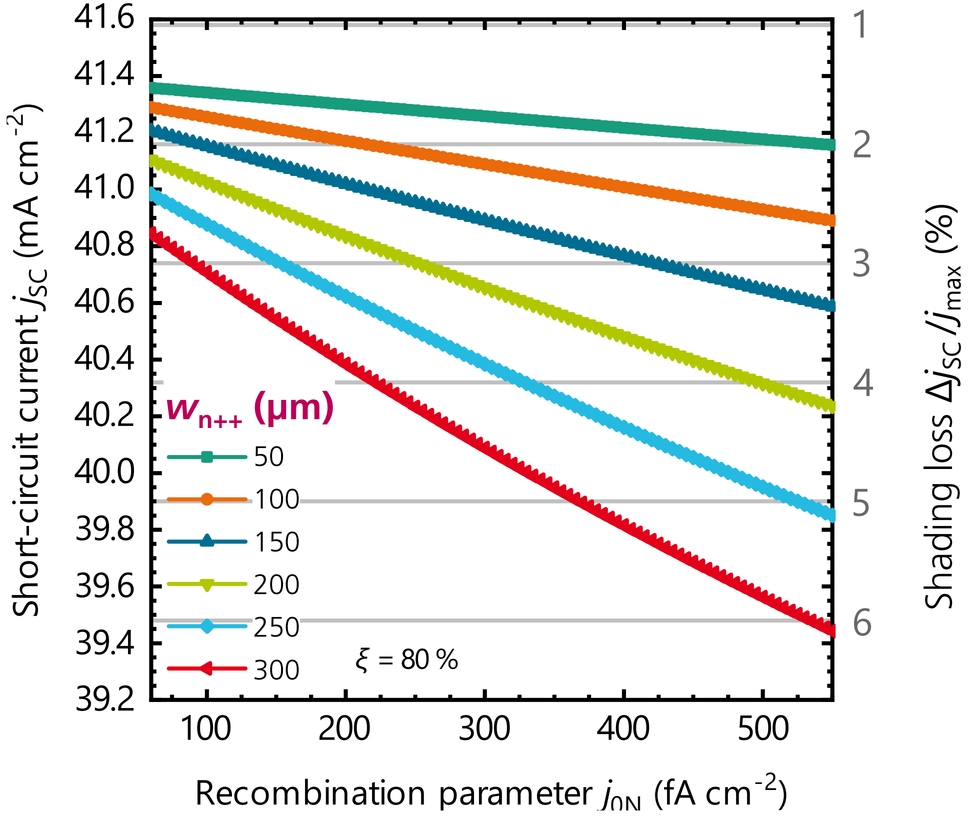
Charge carrier loss due to lateral transport: “Electrical Shading”[1,2]



„Emitter coverage“: $\xi = w_{p++} / l_{pitch}$

2D-Simulation using “SARAH” (Diffusion Resistance)[3]:

https://www.pvlighthouse.com.au/cms/simulation-programs/sarah



[1] W. P. Mulligan and R. M. Swanson, Proceedings of the 13th NREL Crystalline Silicon Workshop, Vail, Colorado, USA, 2003, pp. 30–37

[2] Reichel, C.; Granek, F.; Hermle, M.; Glunz, Stefan W. (2011): *J. Appl. Phys.* 109 (2), S. 24507. DOI: 10.1063/1.3524506.

[3] Saint-Cast, P.; Padilla, M.; Kimmerle, A.; and Reichel, C. (2014): *IEEE Journal of Photovoltaics 4(1)*, pp. 114–121. DOI: 10.1109/jphotov.2013.2287771

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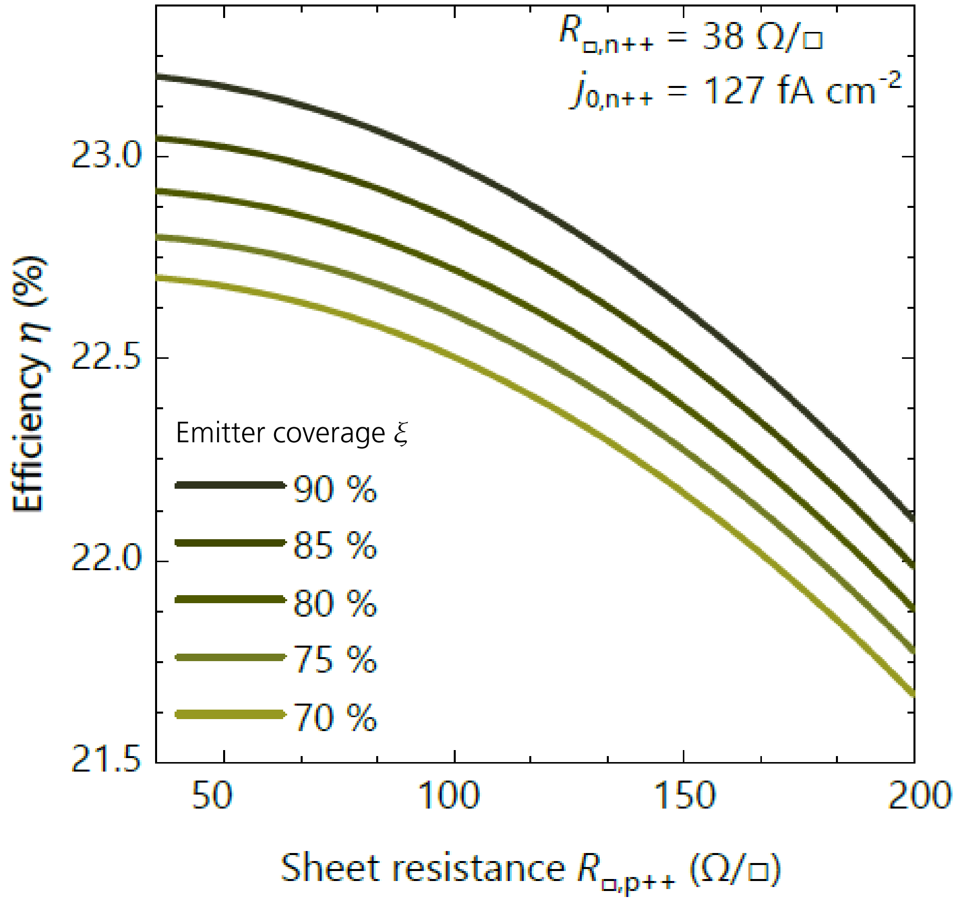
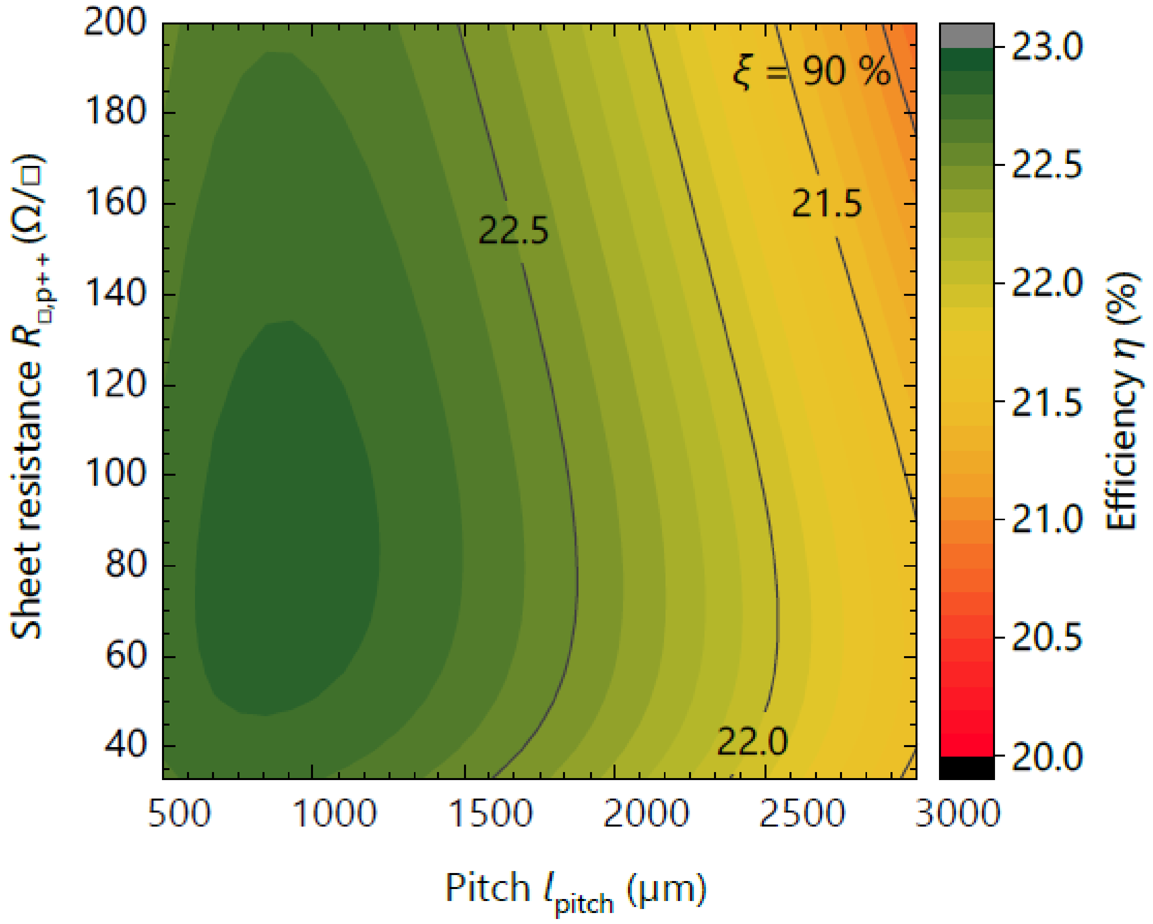
Gapless IBC Solar Cells

Realization of Multi-Parameter Simulation to optimize "Co-Diffused All-Screen-Printed IBC"[1]



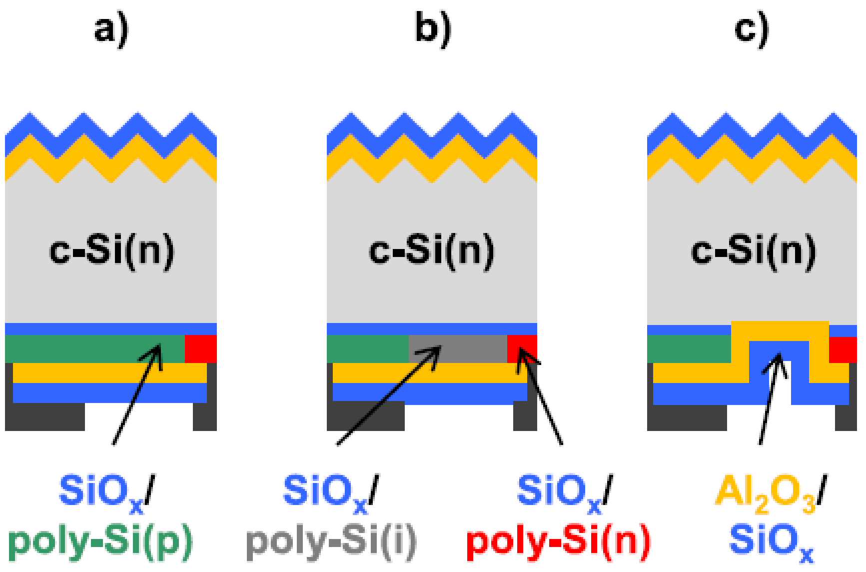


[1] Huyeng, J.D., PhD thesis, 2020. DOI: 10.6094/UNIFR/223536

Next Generation: Implementing Passivating Contacts

TOPCon-IBC Solar Cells[1]

Schematic

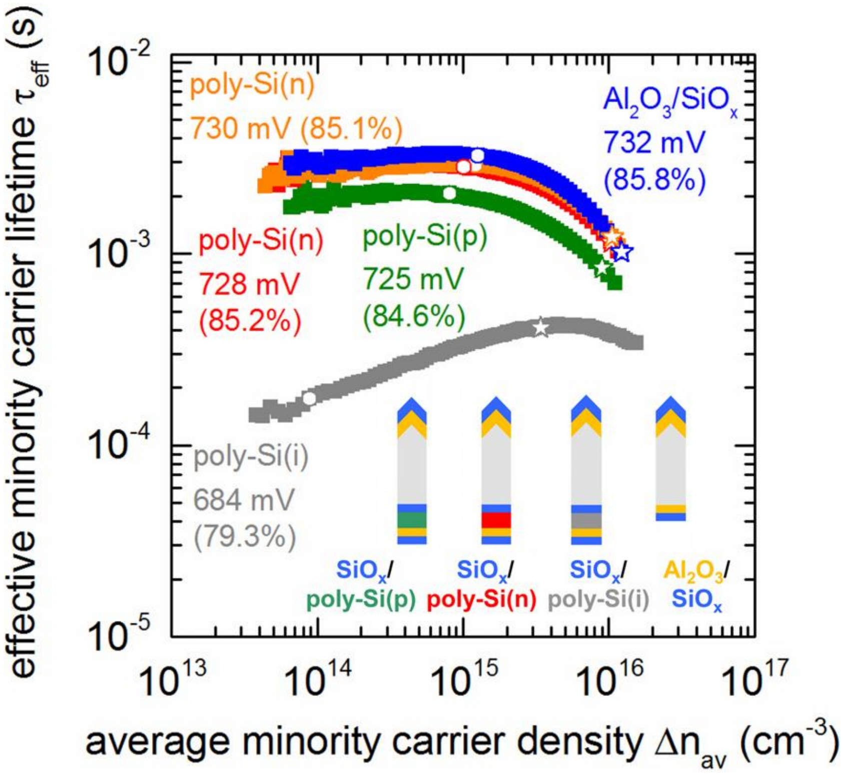


pn junction

pin junction

(passivated) trench

Surface Passivation



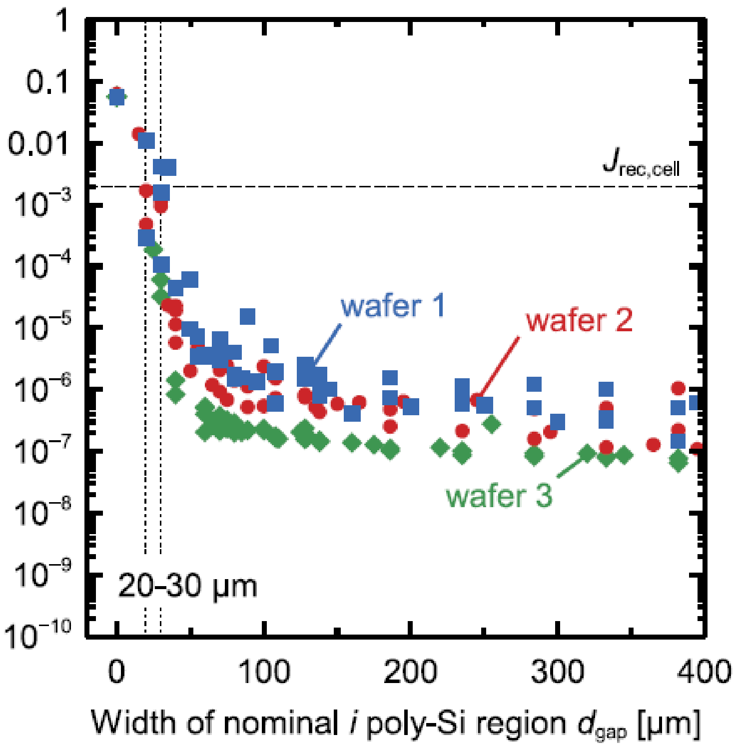
[1] Reichel, C.; Müller, R.; Feldmann, F.; Richter, A.; Hermle, M.; Glunz, S. W. (2017): *J. Appl. Phys.* 122 (18), S. 184502. DOI: 10.1063/1.5004331.

[2] Hollemann, C.; Haase, F.; Rienäcker, M.; *et al.* (2020): *Sci Rep* **10**, *658*. DOI: 10.1038/s41598-019-57310-0.

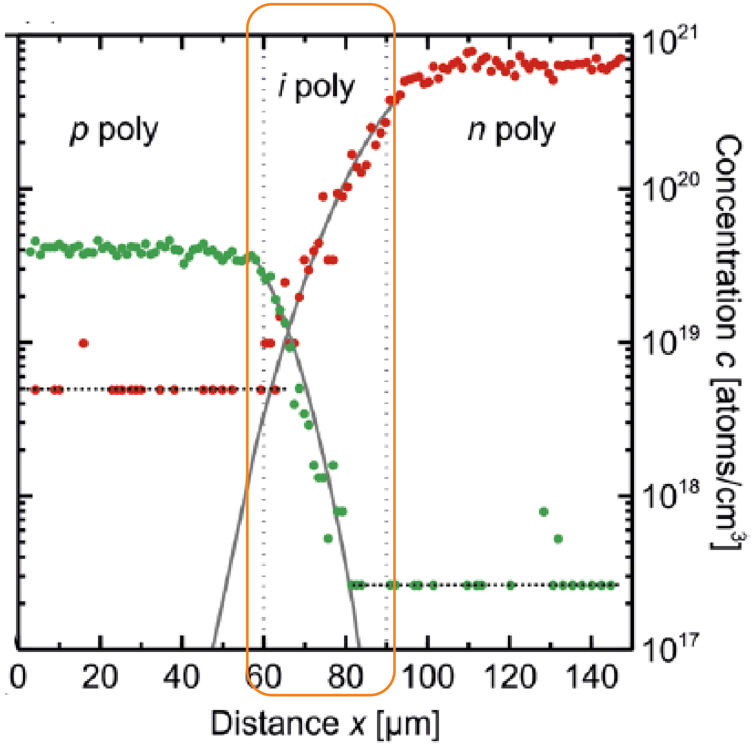
Lateral Diffusion in poly-Si Films

"*pin*" vs "*pn*" Structures – "Nominal" vs. "Realized"

Figures from Hollemann *et al.* [2]



⇒ "*pin*" turned into "*pn*" junction



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[2] Hollemann, C.; Haase, F.; Rienäcker, M.; *et al.* (2020): *Sci Rep* **10**, *658*. DOI: 10.1038/s41598-019-57310-0.

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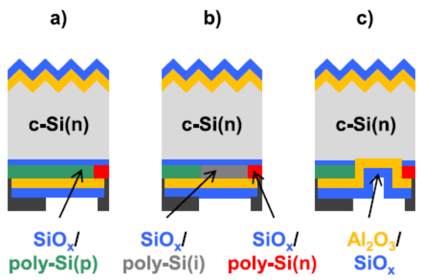
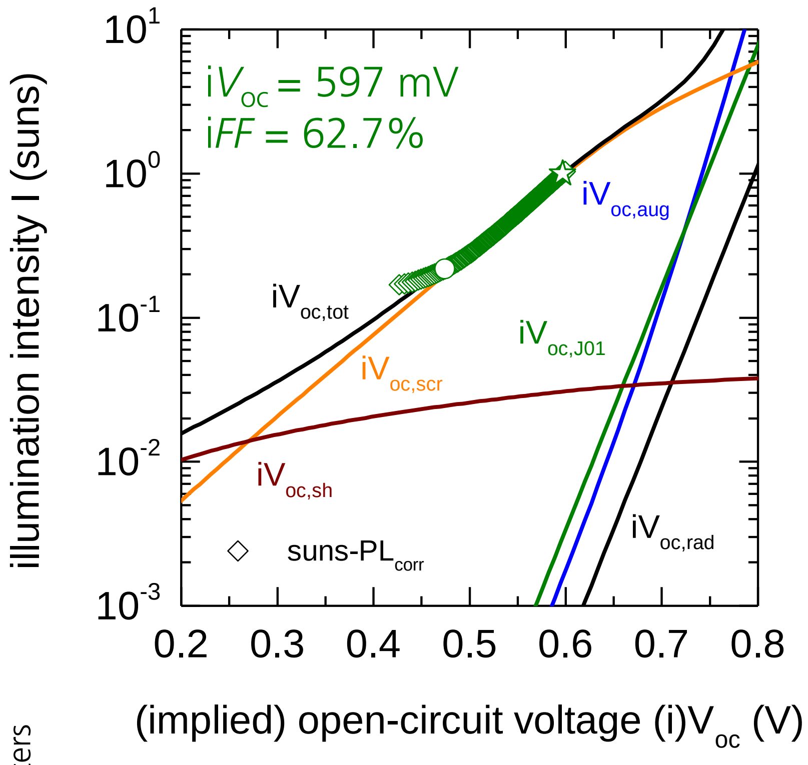
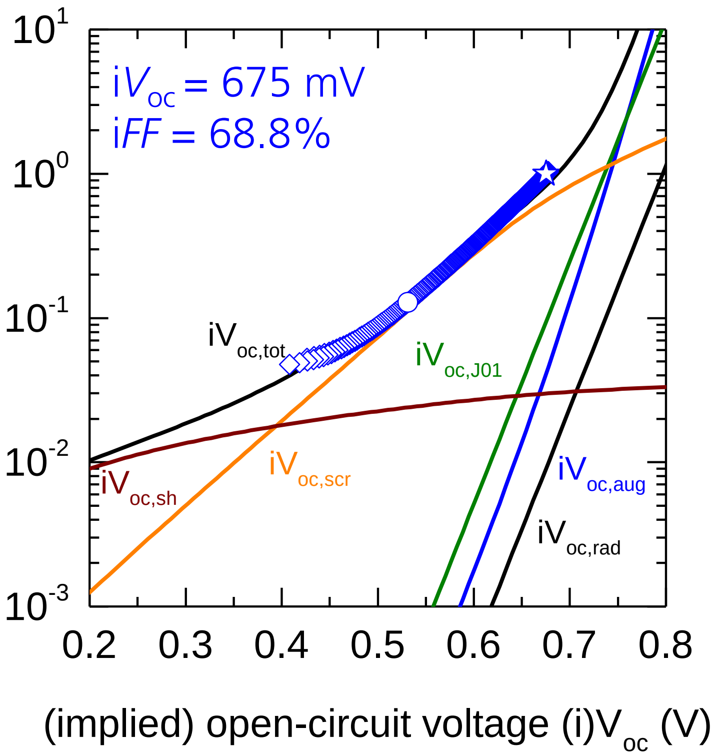
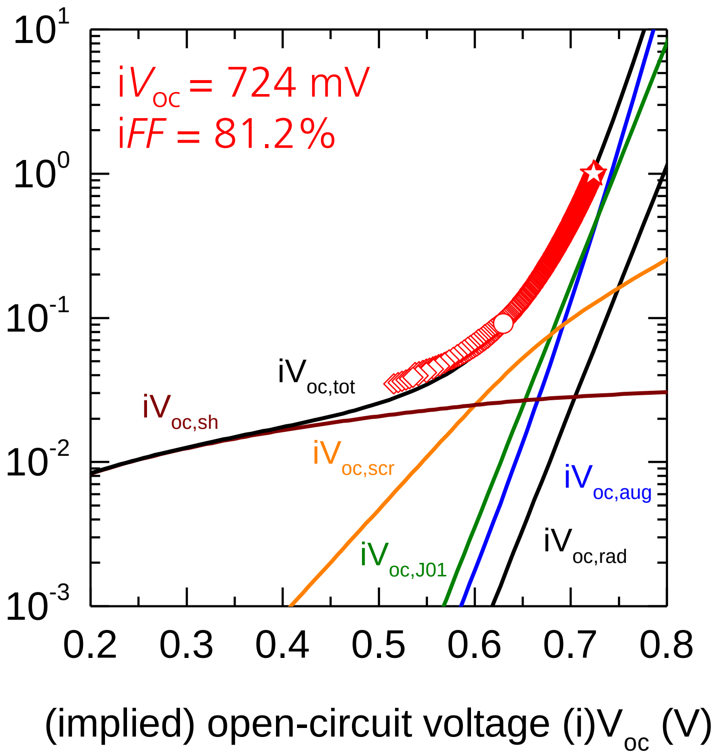
TOPCon-IBC Solar Cells

Influence of the Transition Region (suns-*V*oc Modelling)[1]









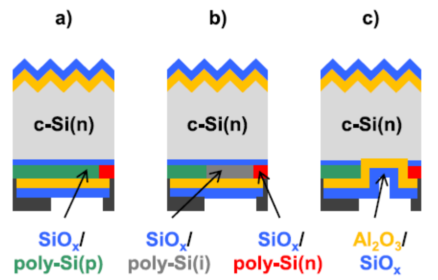
Fit parameters

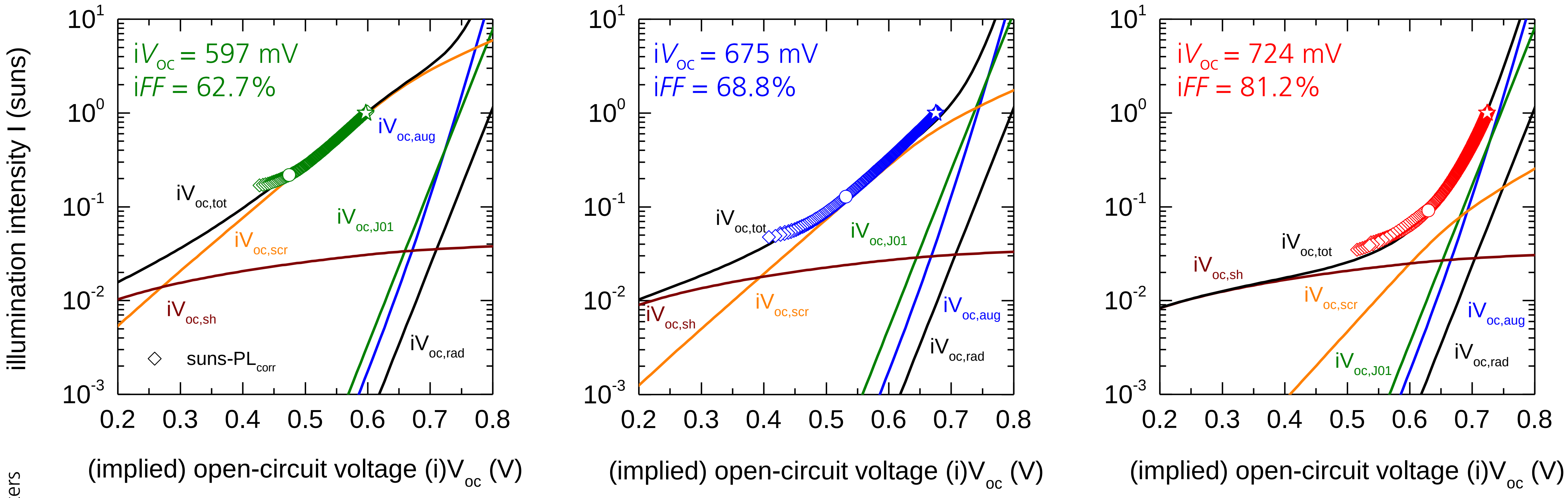
J_{01} = 21 fA/cm²	J_{01} = 28 fA/cm²	J_{01} = 21 fA/cm²
J_{SCR} = 17000 nA/cm²	J_{SCR} = 3600 nA/cm²	J_{SCR} = 40 nA/cm²
R_{shunt} = 0.5 kΩ cm²	R_{shunt} = 0.57 kΩ cm²	R_{shunt} = 0.62 kΩ cm²

[1] Reichel, C.; Müller, R.; Feldmann, F.; Richter, A.; Hermle, M.; Glunz, S. W. (2017): *J. Appl. Phys.* 122 (18), S. 184502. DOI: 10.1063/1.5004331.

TOPCon-IBC Solar Cells

Influence of the Transition Region (suns-V_{oc} Modelling)[1]





Fit parameters

- Lateral "*pn*-junctions" much more problematic for poly-poly contacts[3-5], other than for doped c-Si (s. above)
- Implementation of trenches into TOPCon-IBC to separate poly-Si[1] or optimization of lateral diffusion[2]

[1] Reichel, C.; Müller, R.; Feldmann, F.; Richter, A.; Hermle, M.; Glunz, S. W. (2017): *J. Appl. Phys.* 122 (18), S. 184502. DOI: 10.1063/1.5004331.
[2] Hollemann, C.; Haase, F.; Rienäcker, M.; *et al.* (2020): *Sci Rep* ***10****, 658*. DOI: 10.1038/s41598-019-57310-0.
[3] D. De Ceuster et al., Patent Application US 2009/0308438 A1 (2009), [4] J. Manoliu et al., Solid-State Electronics 15 (1972),
[5] M. Dutoit et al., J. Electrochem. Soc.125 (1978)

Summary

Influence of the Transition Region Between *n*- and *p*-Doped Silicon on IBC Solar Cells

Several design and process options available for IBC solar cells

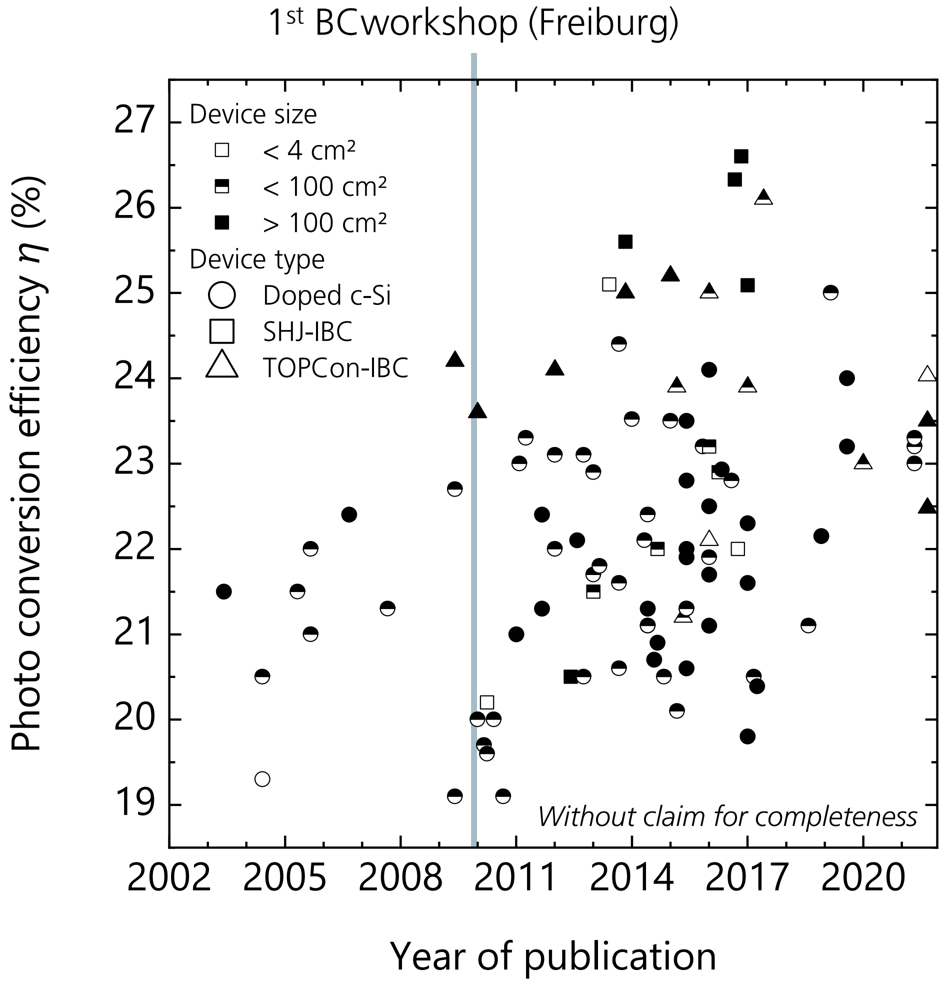
- Optimization and simulation of IBC solar cells often require more details than “simple” solar cells
  - Actual cell performance can derivate unexpectedly
  - Transition region between *n*- and *p*-doped Silicon: Additional lateral and vertical junctions need to be considered
- Gapless solar cells offer significant simplification
  - Process details matter a lot

Next generation: TOPCon-IBC

- Some details change, several fundamentals stay the same
  - Touching poly-poly contacts in the transition region can be severe
- What you see in schematics might tell you even less

BC community

- Many great accomplishments achieved
- Looking forward to results from this workshops



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