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BURST

On the low breakdown voltage of IBC cells

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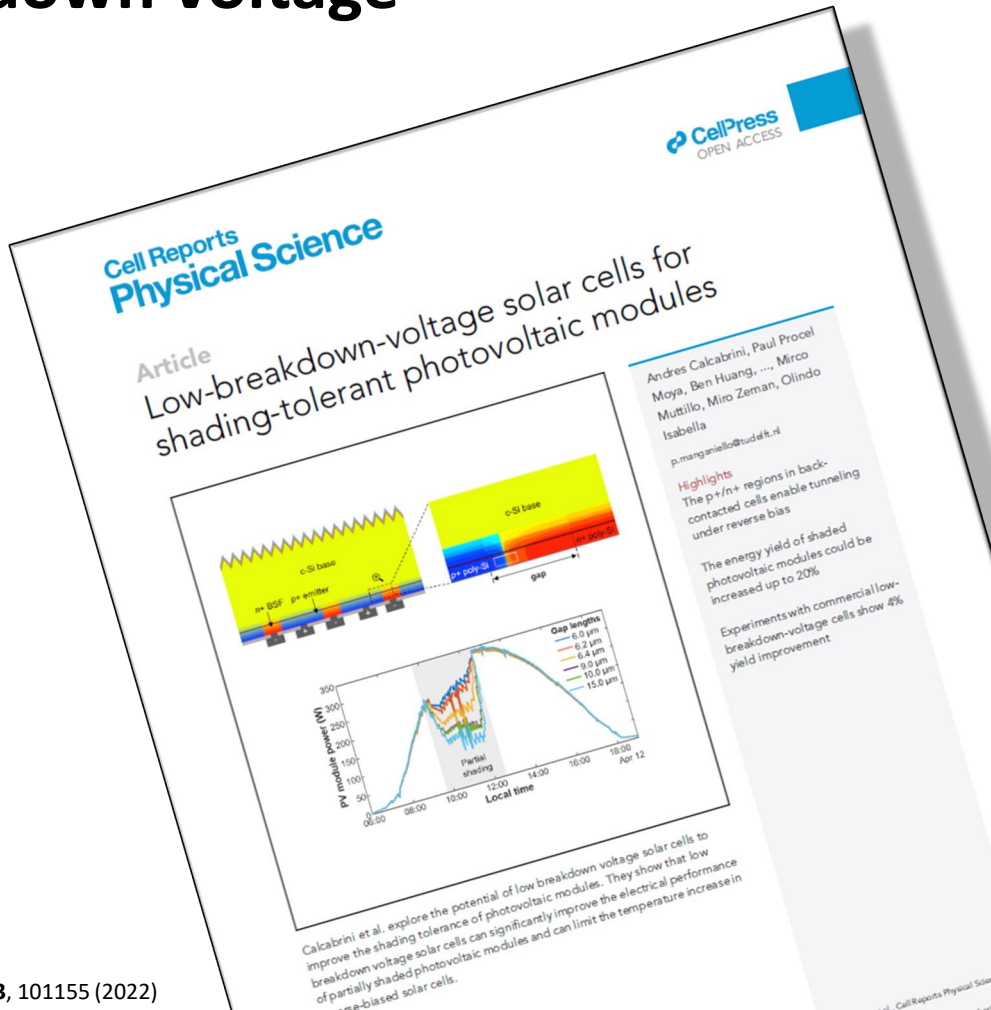
Low breakdown voltage

- **Breakdown physics**
  - IBC advantages over FBC architectures
  - Band to band tunnelling
  - Charge exchange between n+ and p+ regions
- **Energy yield**
  - Shadow tolerant scenarios
  - Experiments: 4% gain for low breakdown voltage
- **Trade off**
  - Breakdown voltage *vs* efficiency
  - *Gap between n+ and p+ regions*



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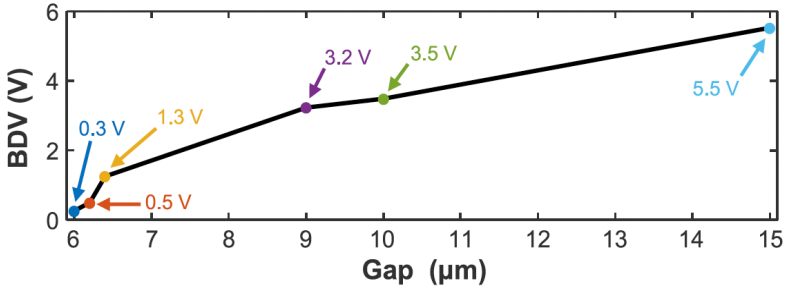
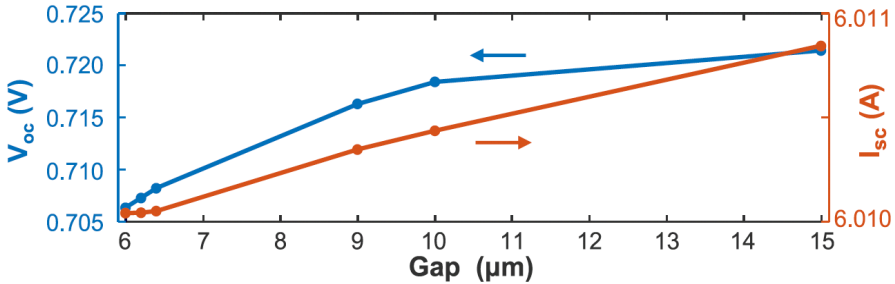
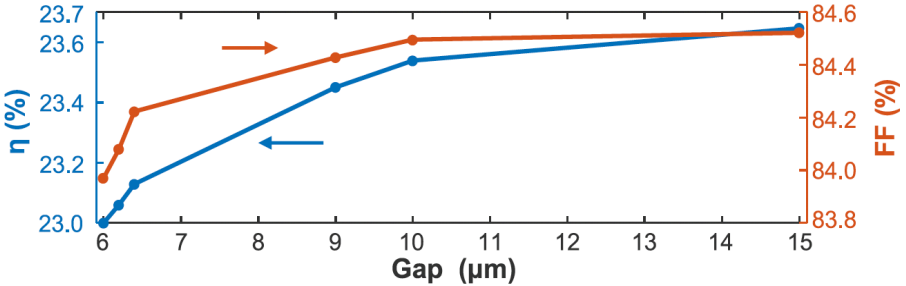
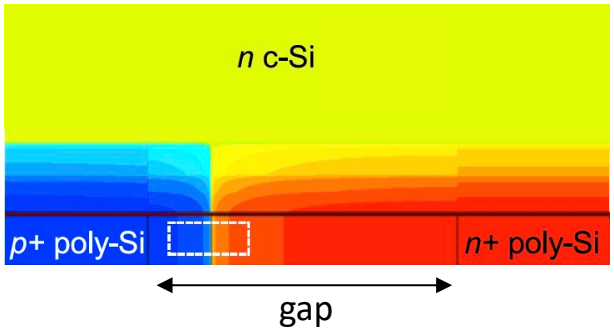
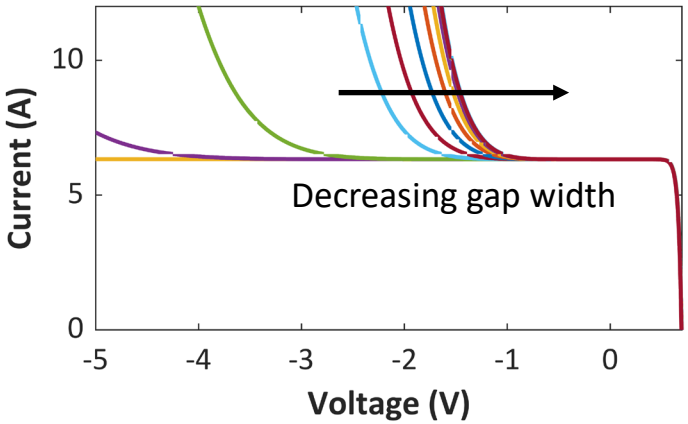
Dopant diffusion and effect of varying gap











A. Calcabrini, et al., *Cell Rep. Phys. Sci.* **3**, 101155 (2022)

Potential of CSPCs in c-Si solar cell architectures

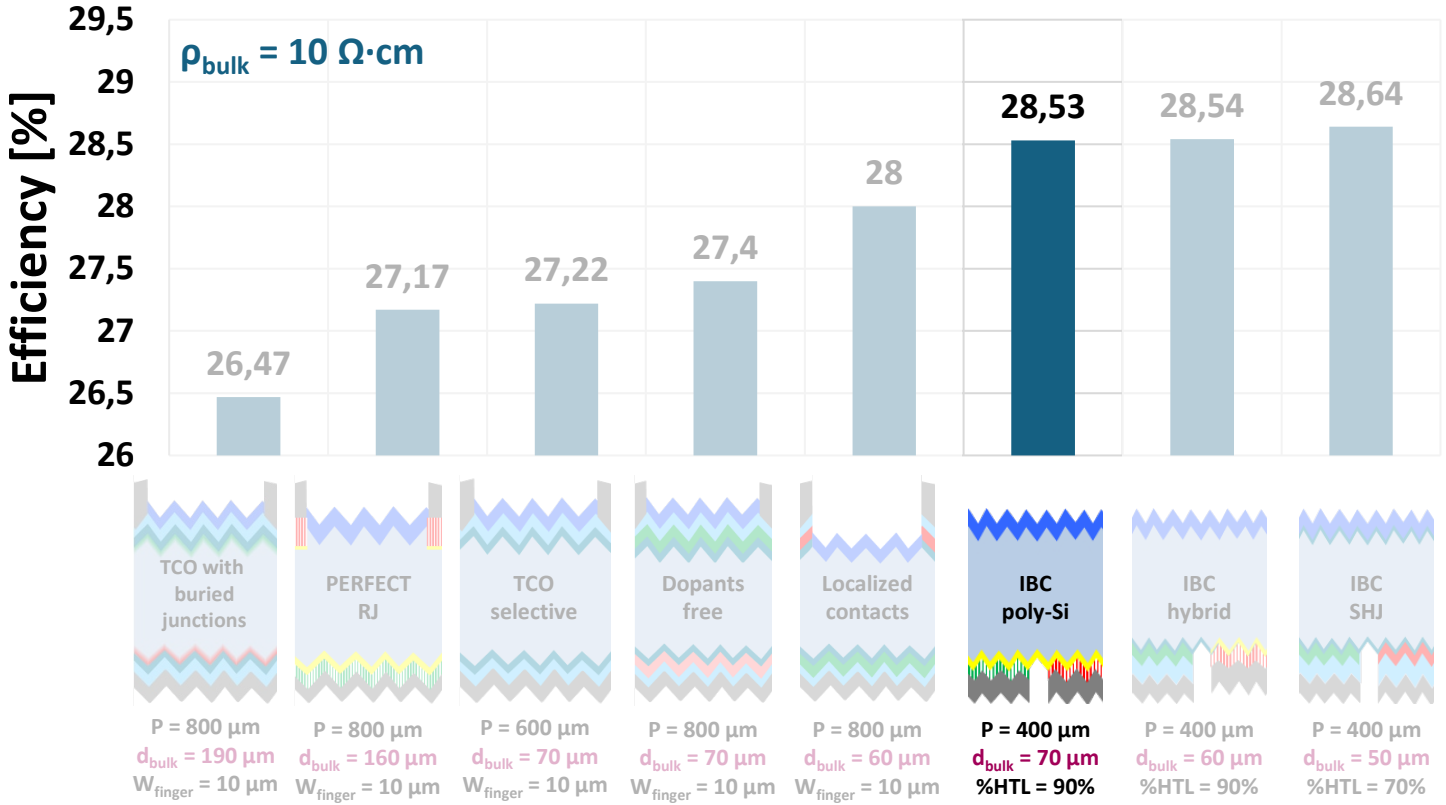
- **Carrier-selective passivating contacts**
  - Transport mechanisms
  - Strike trade-off between J_{SC} and FF

- **Theoretical η peaks depend on**
  - Contacts patterning
  - Wafer thickness
  - Wafer resistivity

- **IBC architectures**
  - *Maximum potential for η close to theoretical limits*

P. Procel Moya, et al., *Sol. Energ. Mater. Sol. Cells*, **285**, 113504 (2025)

Ranking c-Si solar cell architectures



P. Procel Moya, et al., *Sol. Energ. Mater. Sol. Cells*, **285**, 113504 (2025)

Objectives

- **Understand charge transport mechanisms:**
  - **High efficiency IBC poly-silicon solar cells**
  - **Breakdown voltage (BDV)**
- **Calculate BDV**
  - **Ultra-high-efficiency IBC solar cells**
- **Propose design strategies**
  - **Achieve high conversion efficiency**
  - **Simultaneously maintain low BDV**

Modelling method

Input parameters

- Geometry
- ε
- T
- μ
- χ_0
- E_g
- $m_{t(\cdot)}$
- $N_{(\cdot)}$
- DOS
- …

Physical models

- GenPro
- Mobility
- Tunnelling models
- Band gap narrowing
- Recombination mechanisms
  - Radiative
  - Auger
  - SRH
- Dipole layer

Semiconductor equations

Poisson equation

- $\epsilon\nabla^2\phi = -q(p - n + N_D - N_A) - \rho_{trap}$

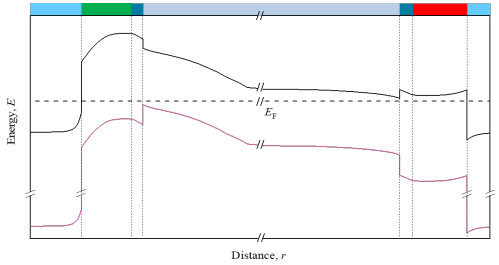
Continuity equation

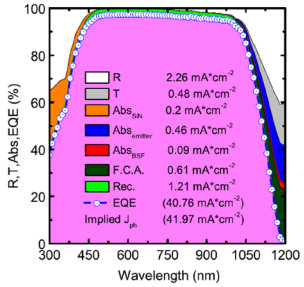
- $\nabla \cdot \overrightarrow{J_{(\cdot)}} = q(R - G) + q\frac{\partial(\cdot)}{\partial t}$

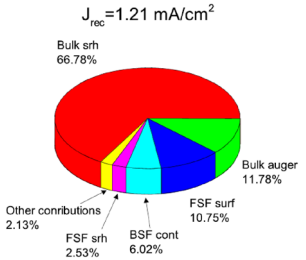
Fermi-Dirac statistics

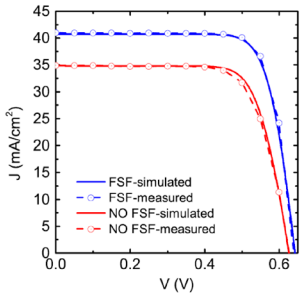
$$f(E) = \frac{1}{1 + exp\left(\frac{E - E_F}{k_B T}\right)}$$

SYNOPSYS®



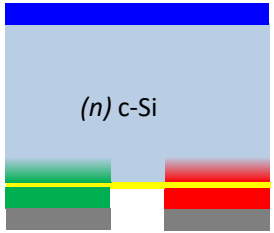


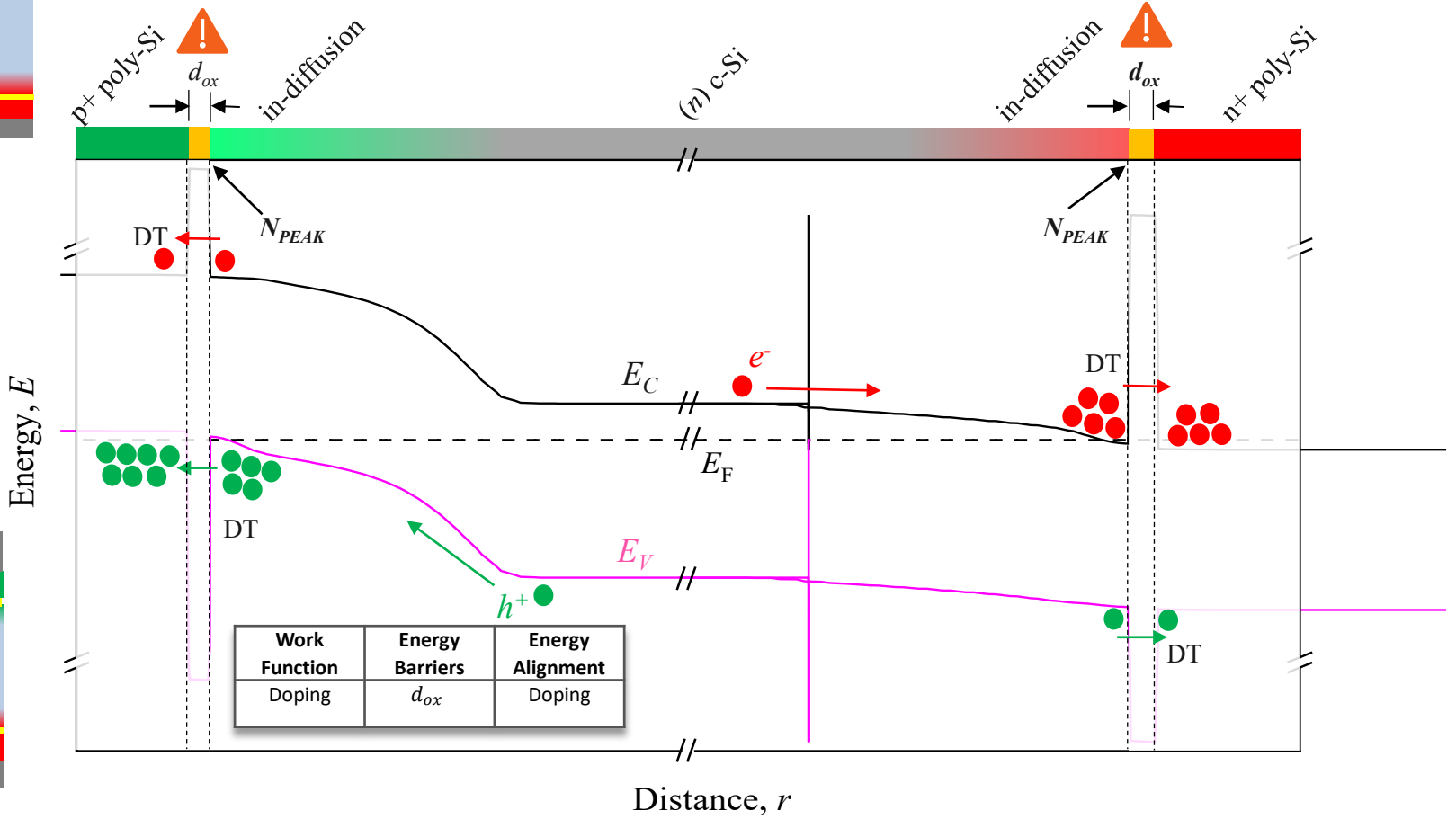


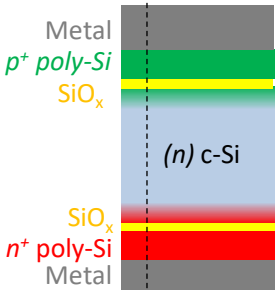


[1] P. Procel, et al., *Prog. Photovoltaics*, **25** (2017)
[2] P. Procel, et al., *Sol. Energy Mater. Sol. Cells*, **186** (2018)
[3] P. Perez-Rodriguez, et al., *ChemSusChem*, **11** (2018)
[4] P. Procel, et al., *Sol. Energy Mater. Sol. Cells*, **200**, (2019)
[5] P. Procel, et al., *IEEE J. Photovoltaics,* **9** (2019)
[6] M. Pomaska, et al., *Prog. Photovoltaics*, **28** (2020)
[7] N. Rezaei, et al., *Prog. Photovoltaics*, **28** (2020)
[8] P. Procel, et al., *Prog. Photovoltaics*, **28** (2020)
[9] M. Köhler, et al., *Nat. Energy*, **6** (2021)
[10] L. Mazzarella, et al., *Prog. Photovoltaics*, **29** (2021)
[11] L.-L. Senaud, et al., *J. Appl. Phys.*, **129** (2021)
[12] J. C. Ortiz Lizcano, et al., *Prog. Photovoltaics*, **30** (2022)
[13] R. van Heerden, et al., *Front. Photonics*, **3** (2022)
[14] L. Cao, et al., *Prog. Photovoltaics* (2022)
[15] A. Calcabrini, et al., *Cell Reports Phys. Sci.*, **3** (2022)
[16] H. Lin, et al., *Nat. Energy*, **8** (2023)
[17] Y. Zhao, et al., *Sol. Energy Mater. Sol. Cells*, **258** (2023)
[18] R. Santbergen, et al., *IEEE Journal of Photovoltaics*, **7** (2017)

Working principle: Charge collection

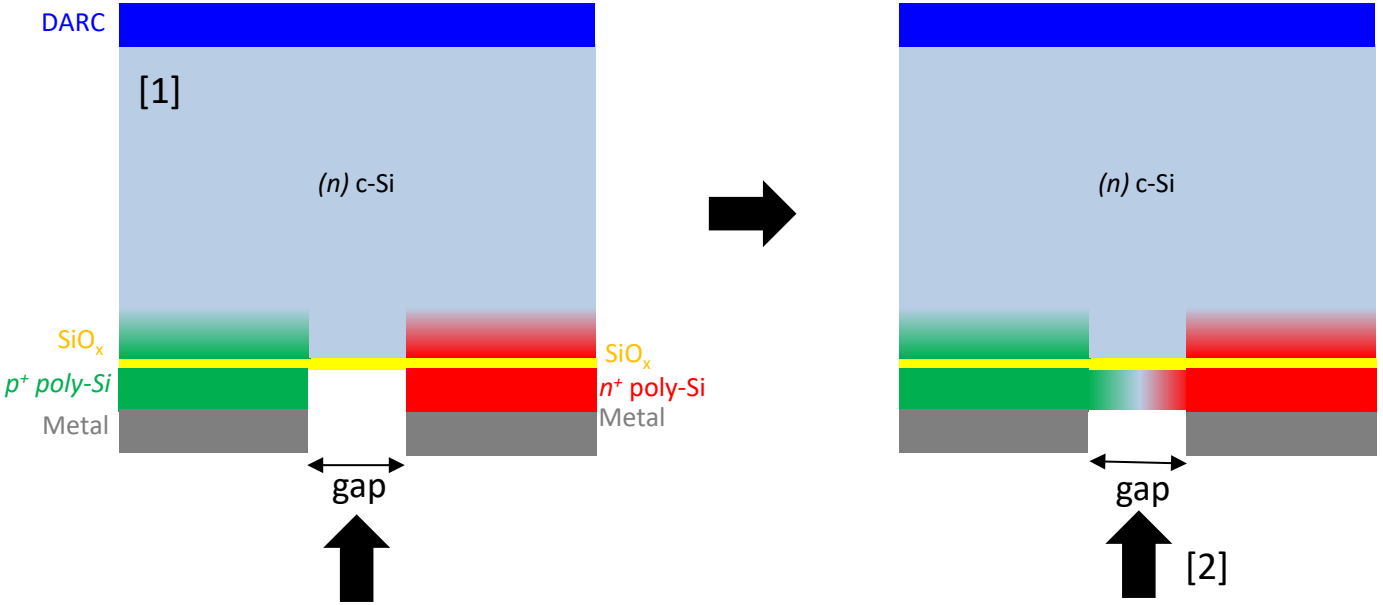






P. Procel, et al., *IEEE J. Photovolt.*, **9** (2019)

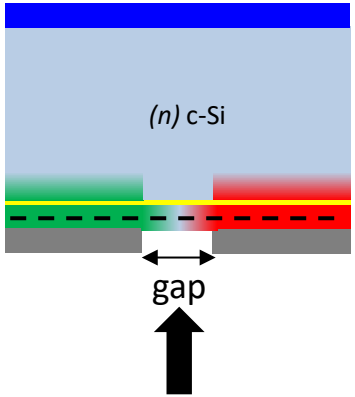
IBC poly-Si CSC

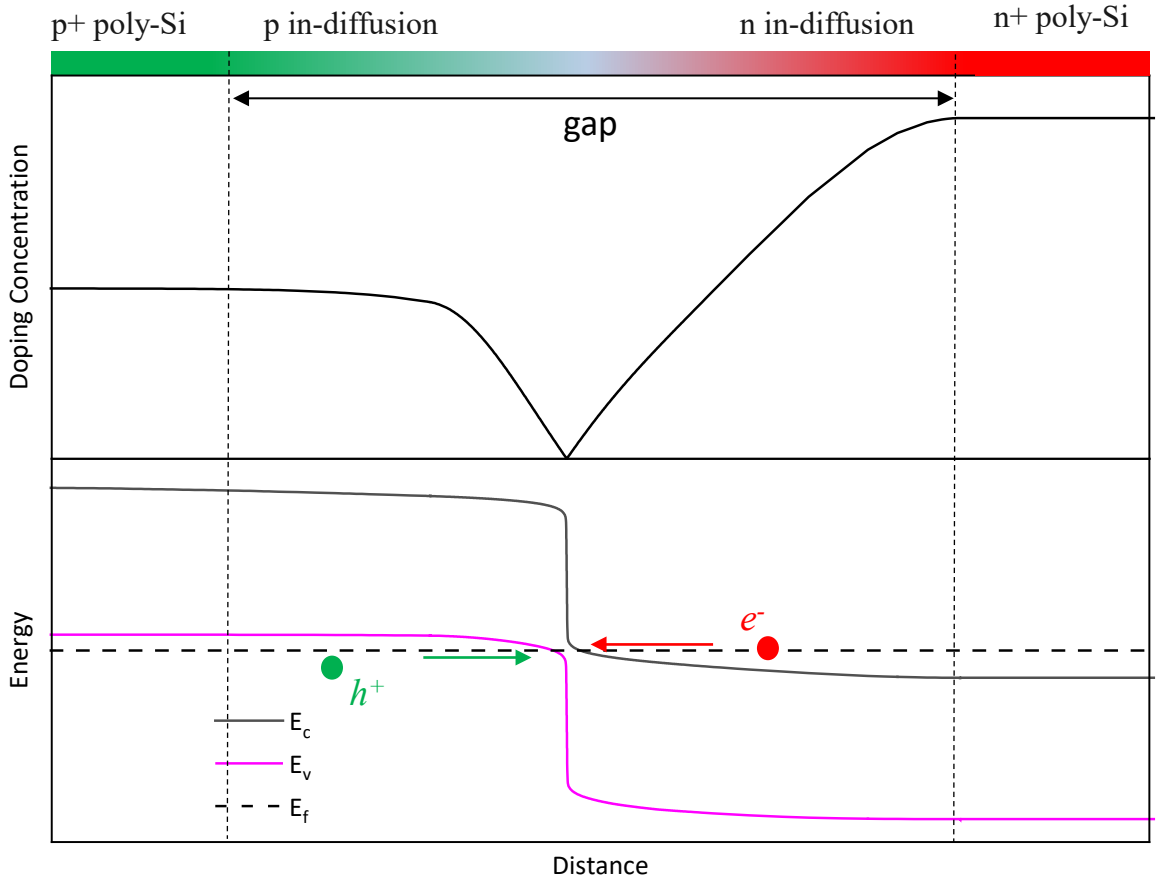


Low breakdown voltage

[1] P. Procel Moya, et al., *Sol. Energ. Mater. Sol. Cells*, **285**, 113504 (2025)
[2] A. Calcabrini, et al., *Cell Rep. Phys. Sci.* **3**, 101155 (2022)

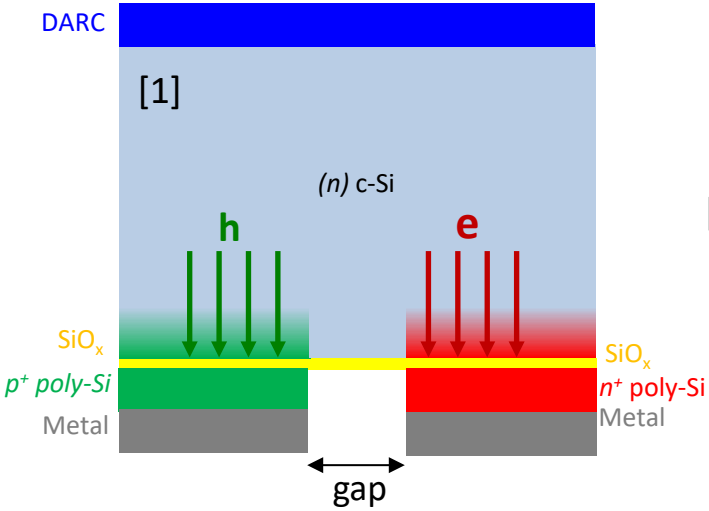
Working principle: Breakdown voltage

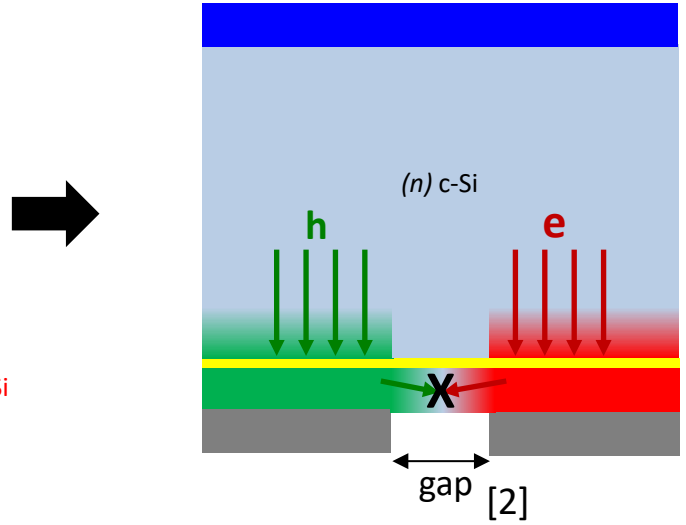




[1] A. Calcabrini, et al., *Cell Rep. Phys. Sci.* **3**, 101155 (2022)

IBC poly-Si CSC





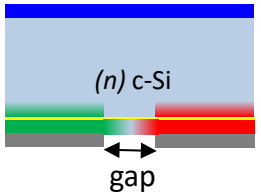
J_{sc} (mA/cm²)	V_{oc} (V)	FF (%)	η (%)
42.51	0.759	88.44	28.53

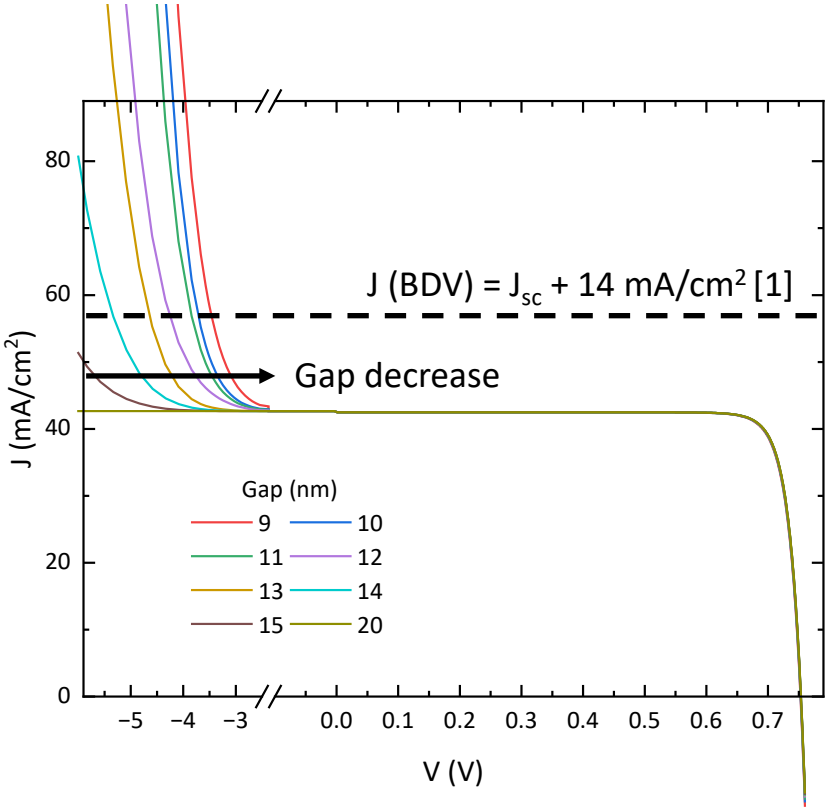
[3]

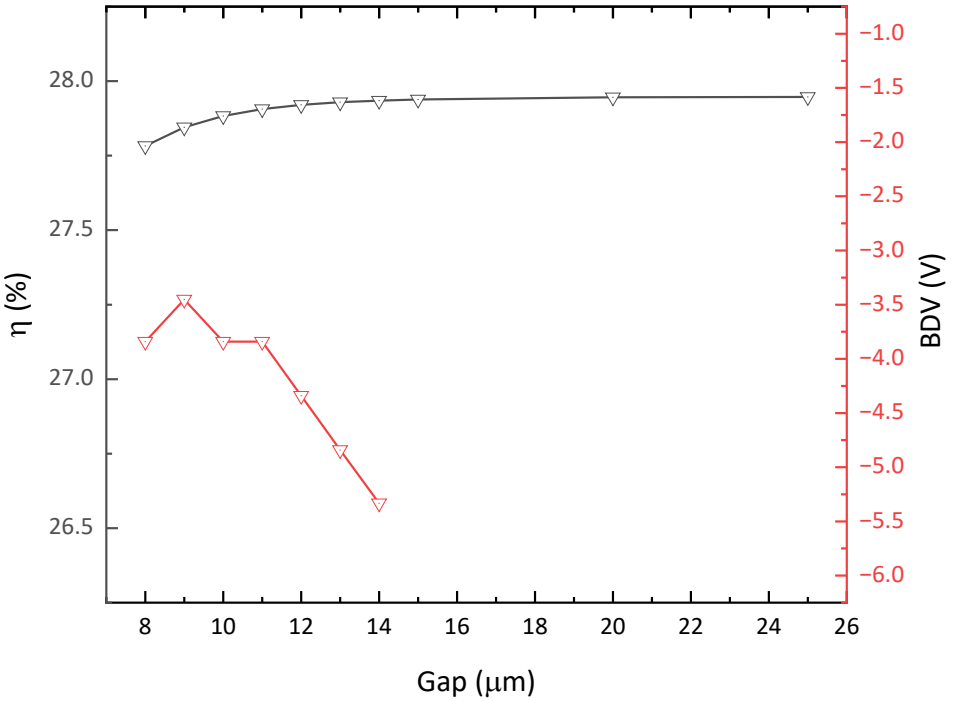
J_{sc} (mA/cm²)	V_{oc} (V)	FF (%)	η (%)
42.48	0.754	87.29	27.95

[1] P. Procel Moya, et al., *Sol. Energ. Mater. Sol. Cells*, **285**, 113504 (2025)
[2] A. Calcabrini, et al., *Cell Rep. Phys. Sci.* **3**, 101155 (2022)
[3] L. Black, et al., *Sol. Energ. Mater. Sol. Cells,* **295**, 113985 (2026)

BDV *vs* η

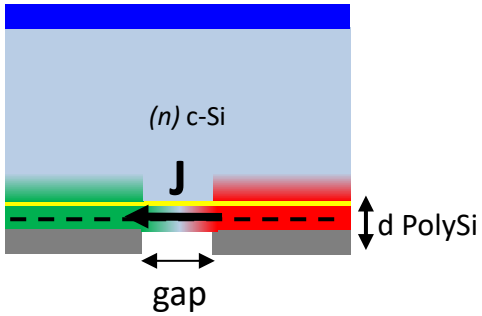


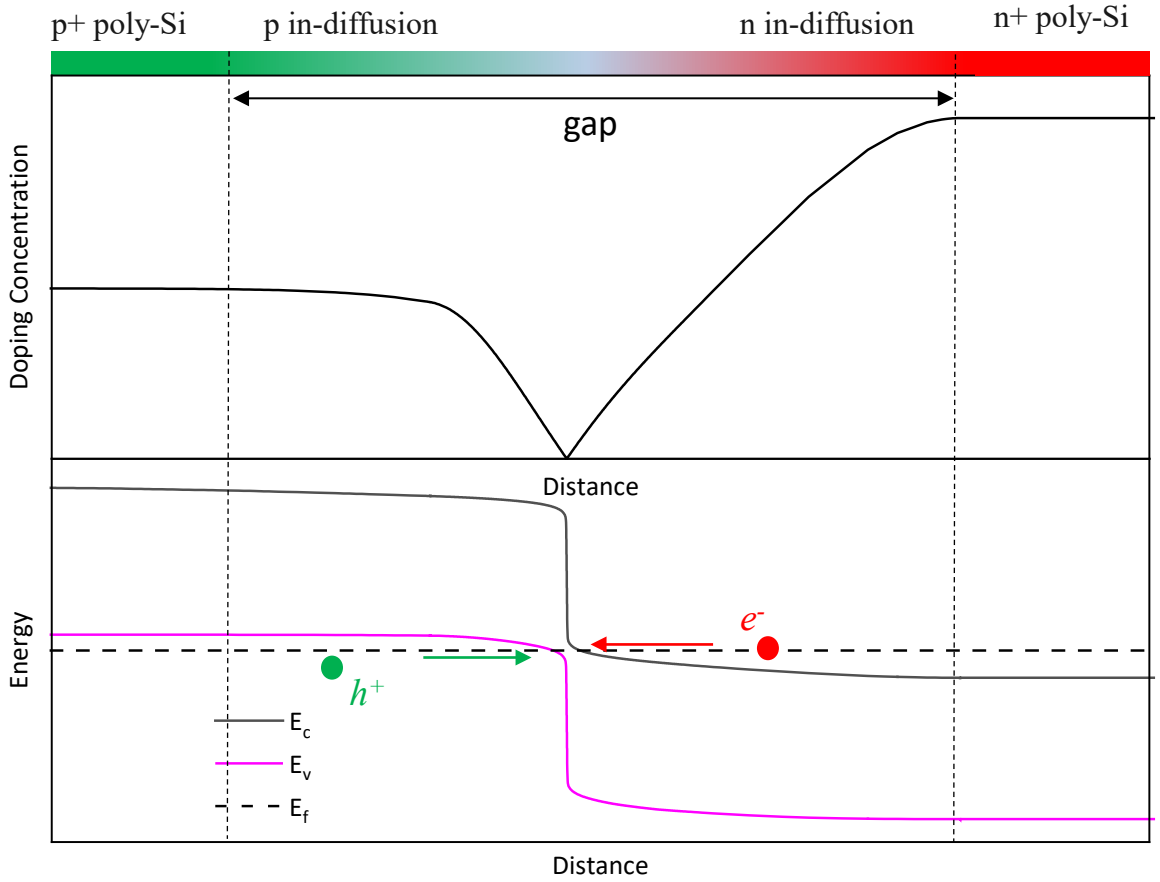




[1] A. Calcabrini, et al., *Cell Rep. Phys. Sci.* **3**, 101155 (2022)

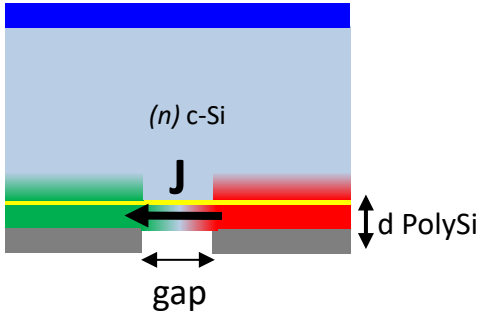
Working principle: BDV

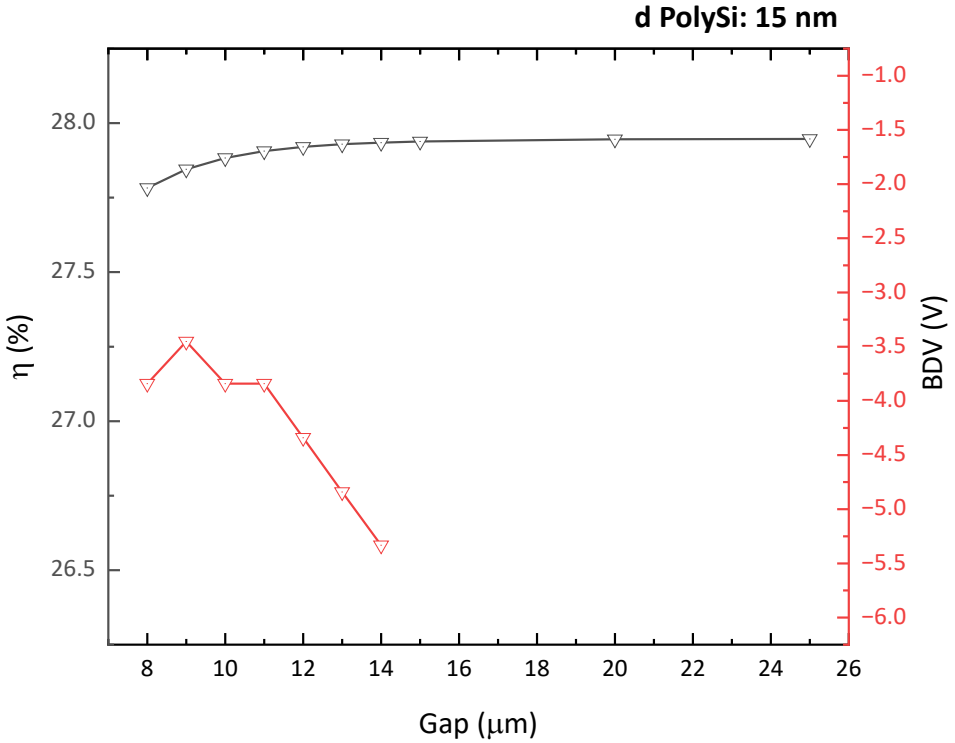




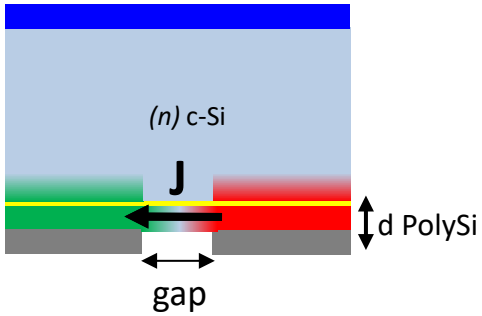
[1] A. Calcabrini, et al., *Cell Rep. Phys. Sci.* **3**, 101155 (2022)

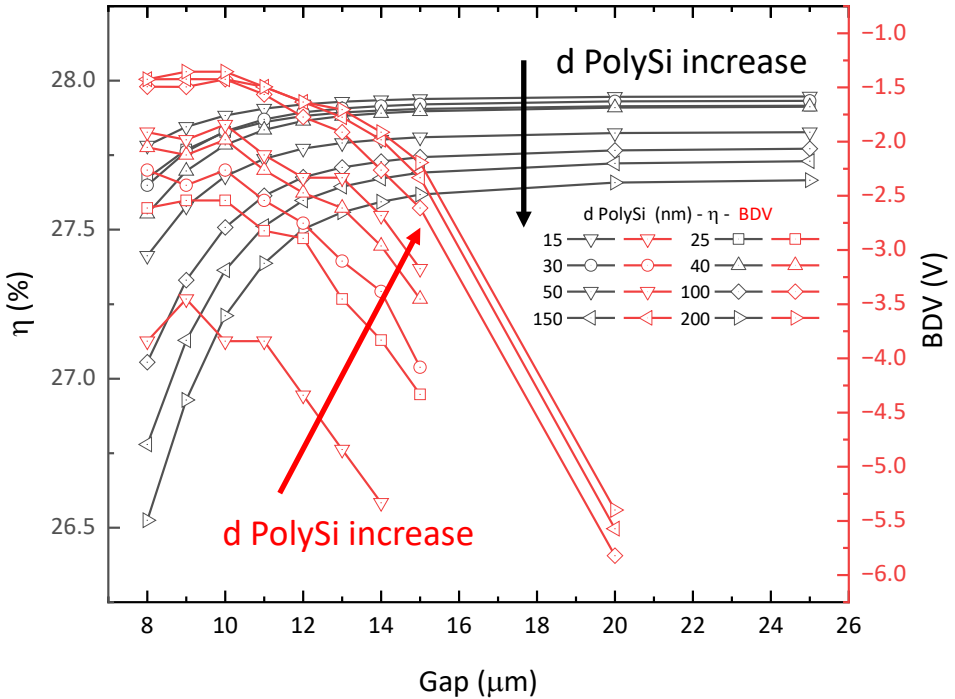
BDV and η


(n) c-Si
J
d PolySi
gap

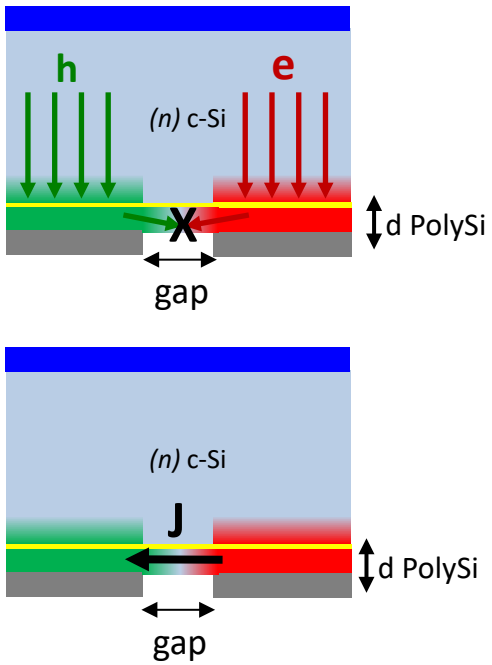

d PolySi: 15 nm
η (%)
BDV (V)
Gap (μm)
28.0
27.5
27.0
26.5
−1.0
−1.5
−2.0
−2.5
−3.0
−3.5
−4.0
−4.5
−5.0
−5.5
−6.0
8
10
12
14
16
18
20
22
24
26

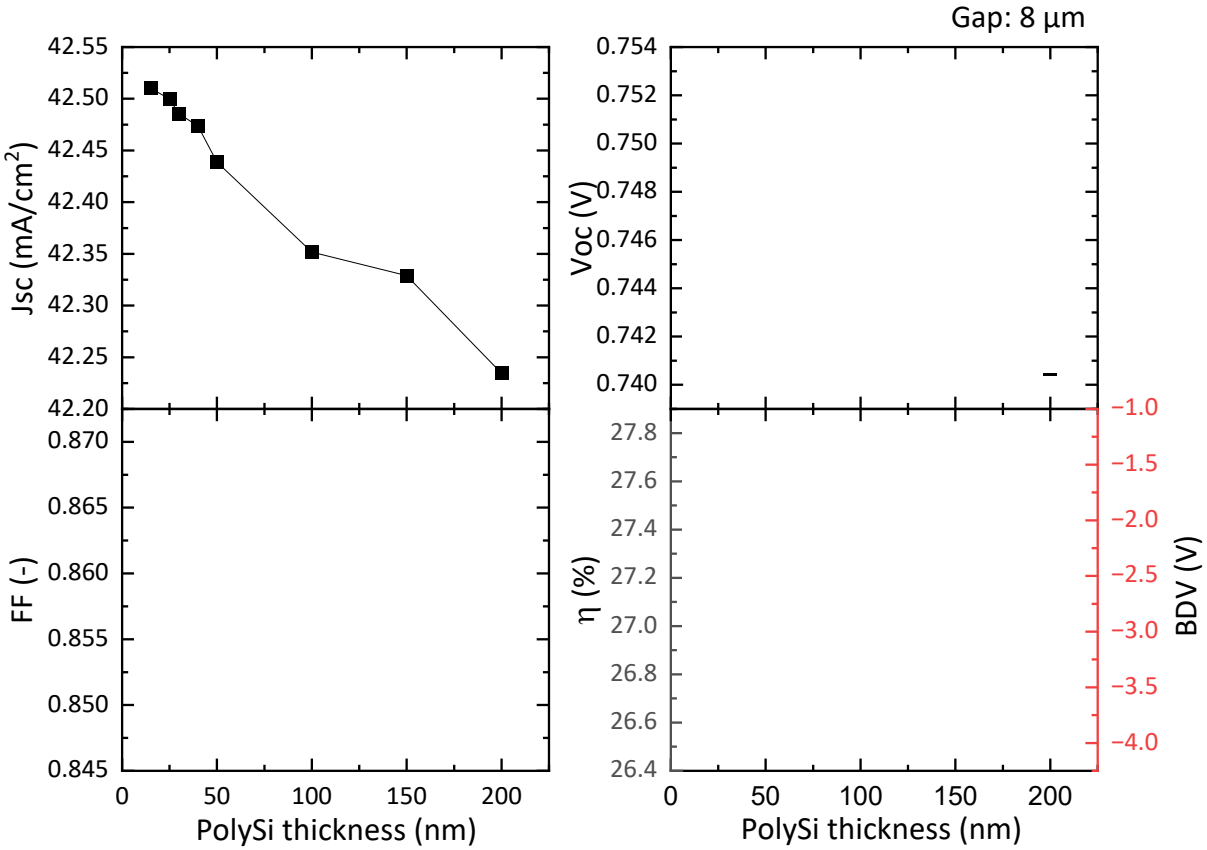
BDV and η


(n) c-Si
J
d PolySi
gap

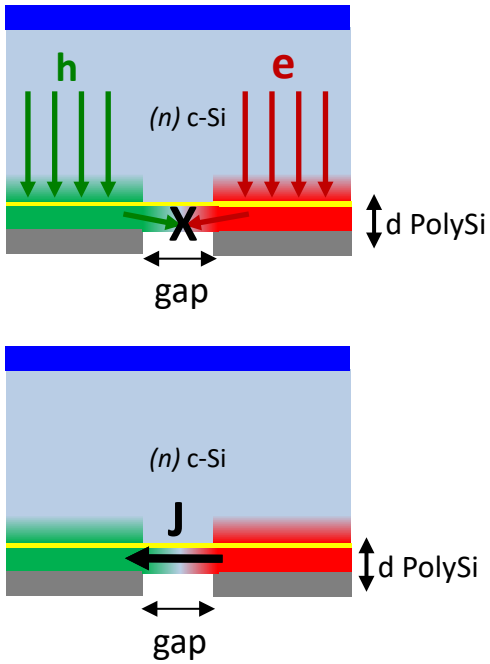

d PolySi increase
d PolySi increase
d PolySi (nm) - η - BDV
15
25
30
40
50
100
150
200
η (%)
BDV (V)
Gap (μm)
28.0
27.5
27.0
26.5
8
10
12
14
16
18
20
22
24
26
−1.0
−1.5
−2.0
−2.5
−3.0
−3.5
−4.0
−4.5
−5.0
−5.5
−6.0

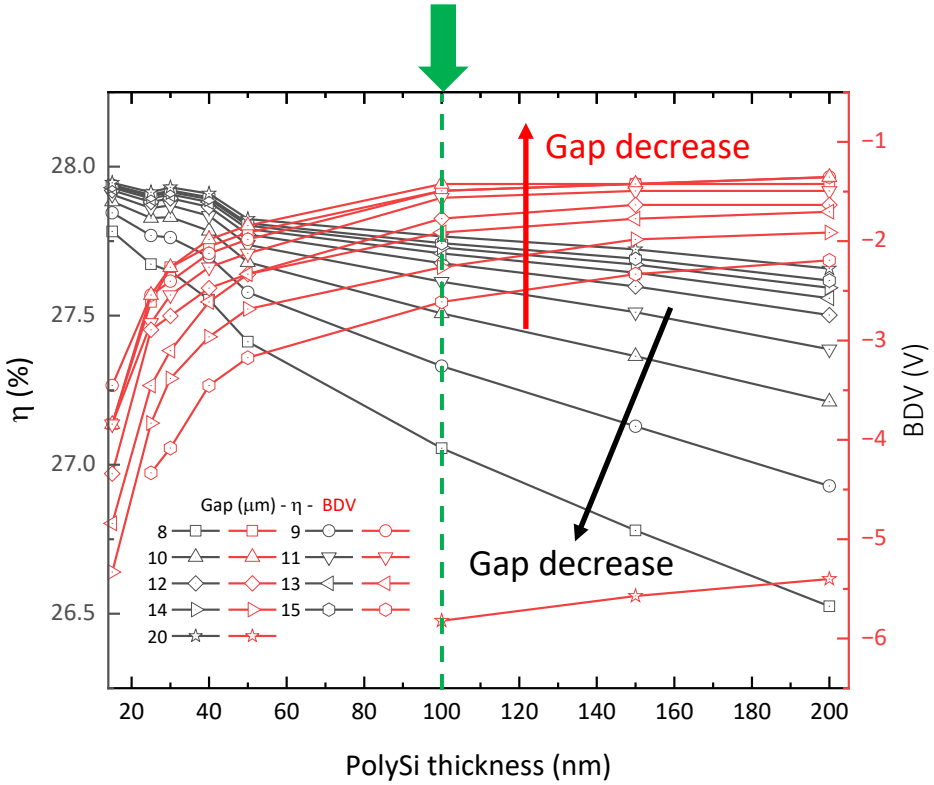
BDV and η: polySi thickness



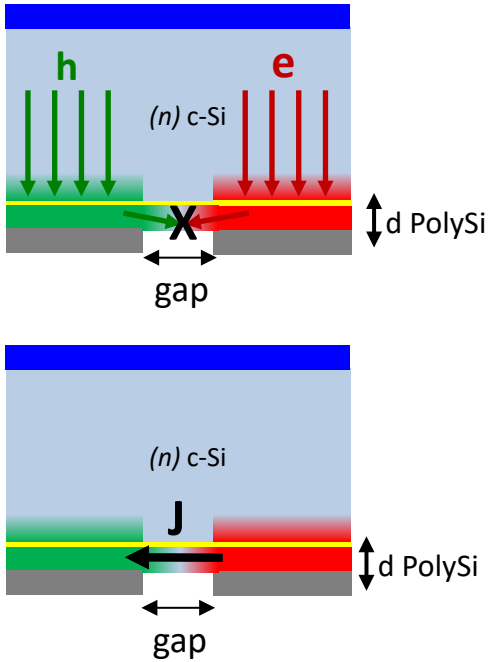


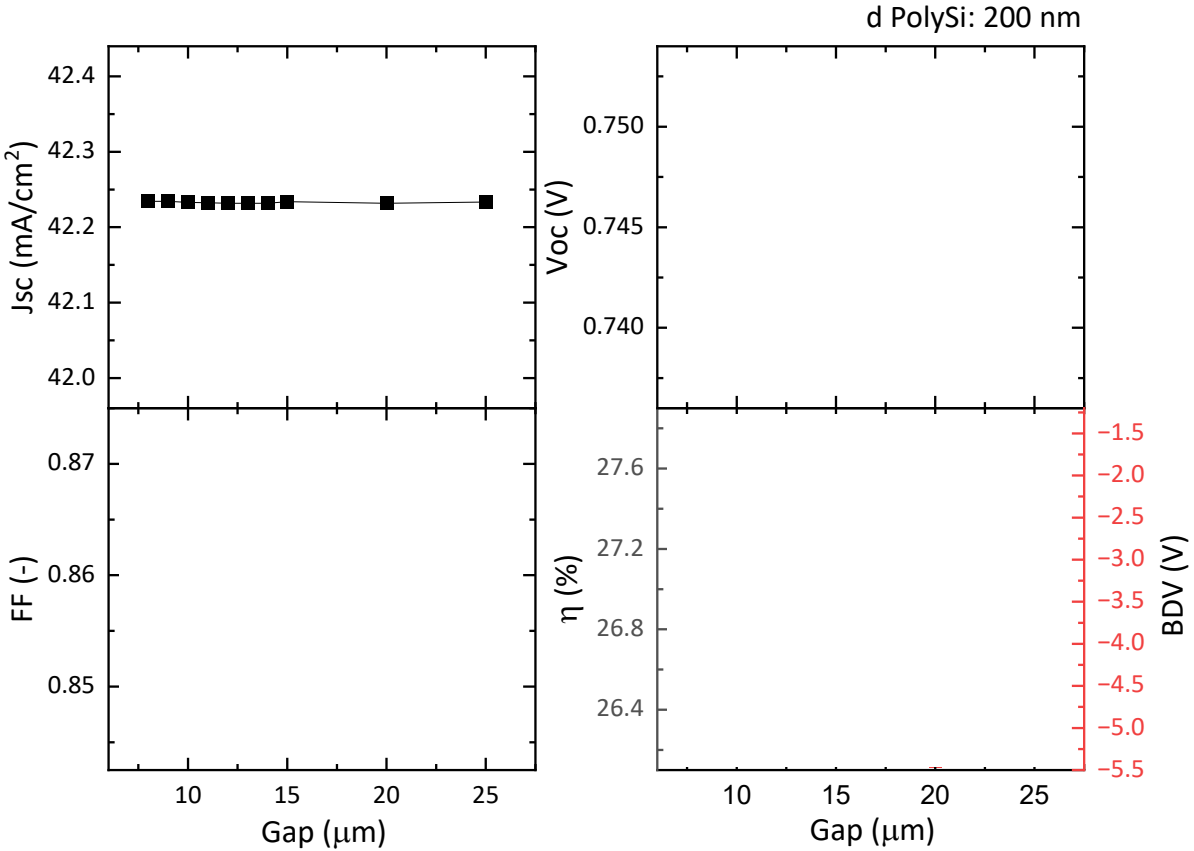
BDV and η: polySi thickness



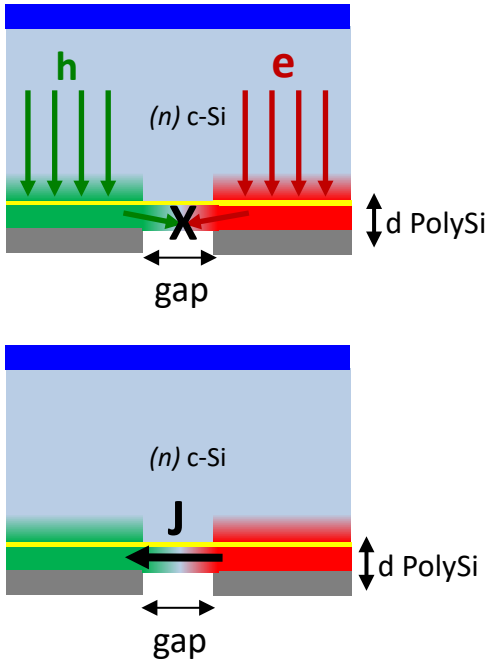


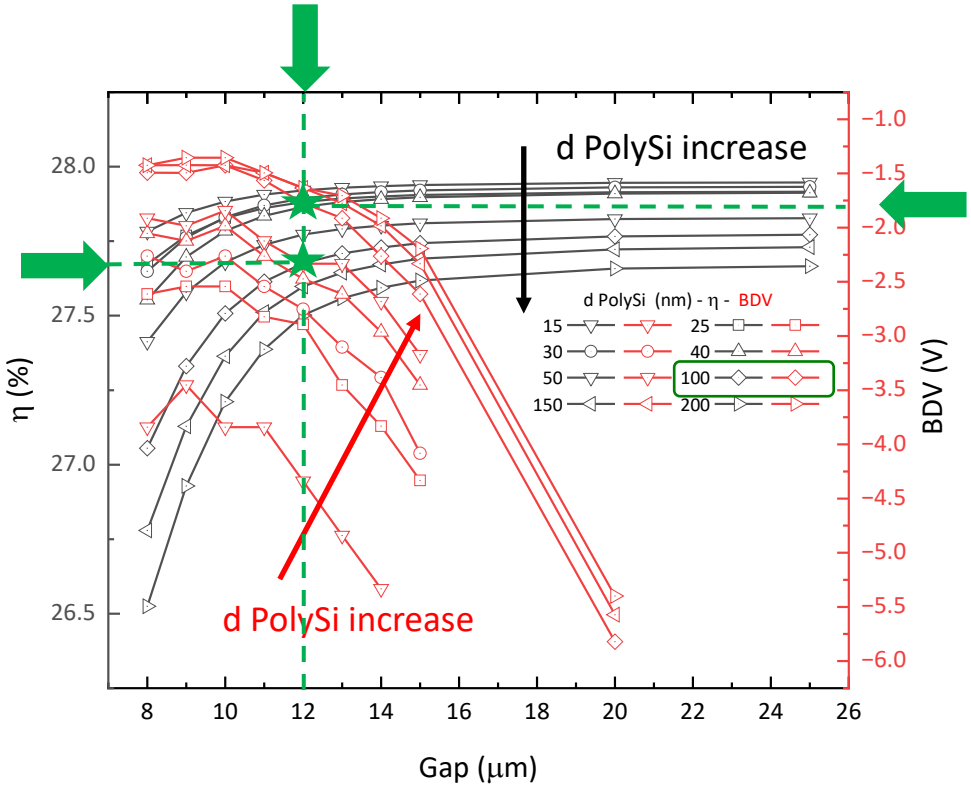
BDV and η: Gap


h
e
(n) c-Si
X
d PolySi
gap
(n) c-Si
J
d PolySi
gap


d PolySi: 200 nm
Jsc (mA/cm2)
42.4
42.3
42.2
42.1
42.0
Voc (V)
0.750
0.745
0.740
FF (-)
0.87
0.86
0.85
η (%)
27.6
27.2
26.8
26.4
BDV (V)
−1.5
−2.0
−2.5
−3.0
−3.5
−4.0
−4.5
−5.0
−5.5
10
15
20
25
Gap (μm)
10
15
20
25
Gap (μm)

BDV and η: Gap

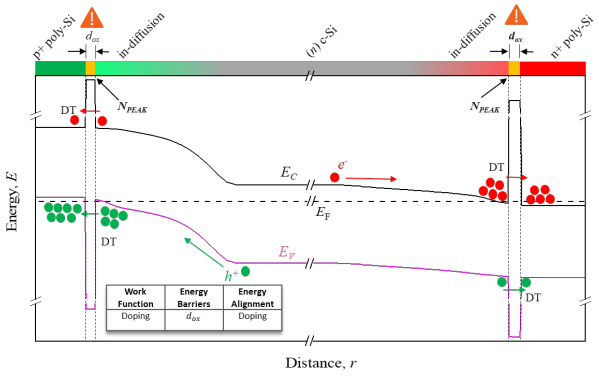


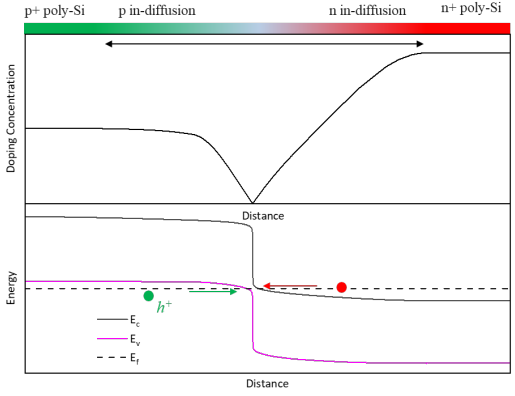


★ η: 27.68 % & BDV: -1.77 V

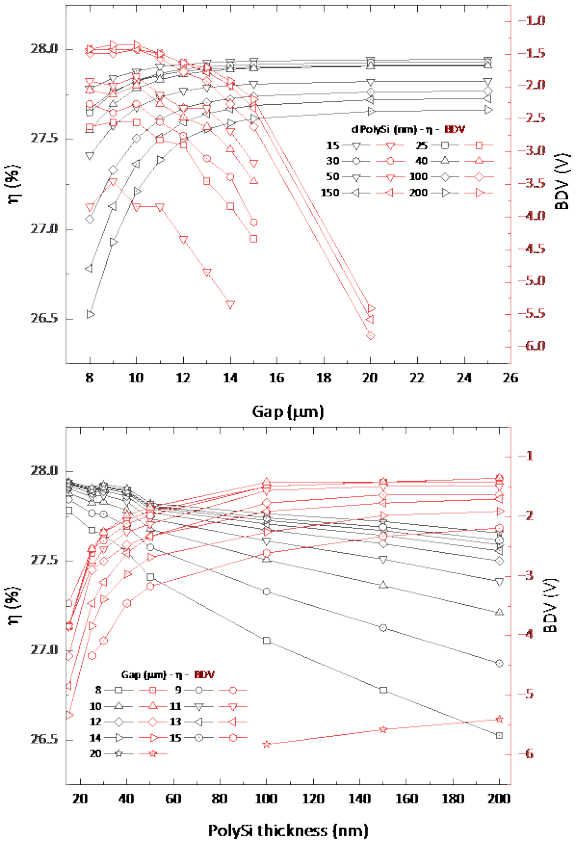
Conclusions

Charge transport

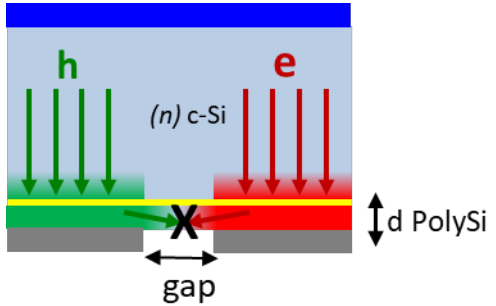


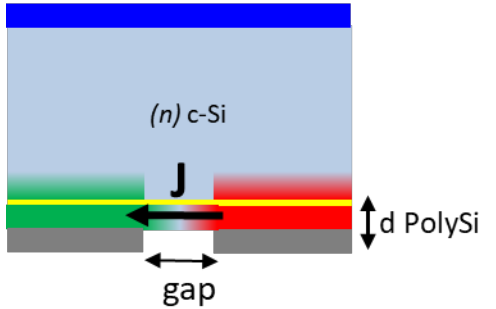


Calculate BDV & η



Propose design strategies





η: 27.68 % & BDV: -1.77 V

Thank you for your attention!

TU Delft Institutes

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e-Refinery

AgTech

TU Delft Climate Action Programme

PVMD funding

Rijksdienst voor Ondernemend Nederland

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Contacts

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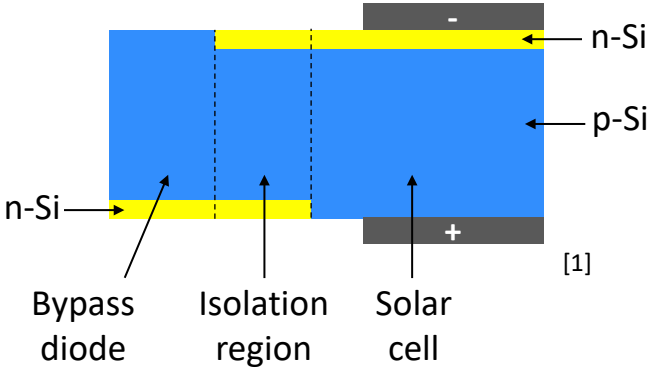
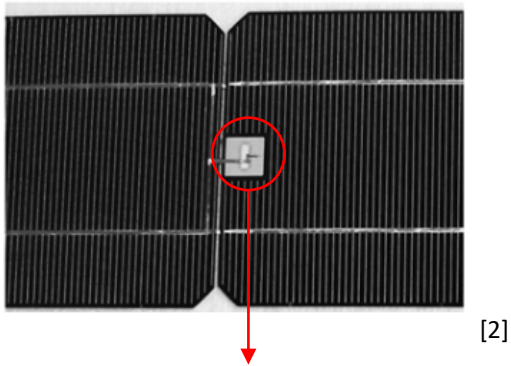
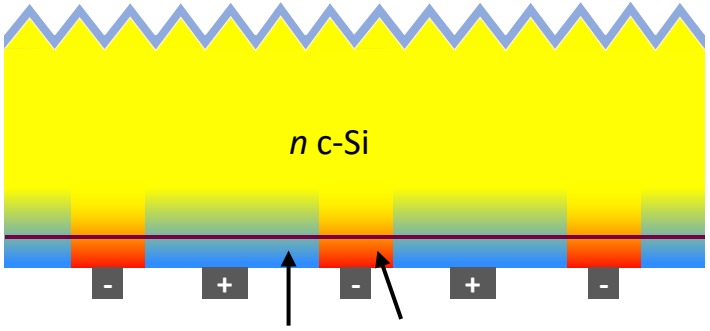
Integrated bypass diodes

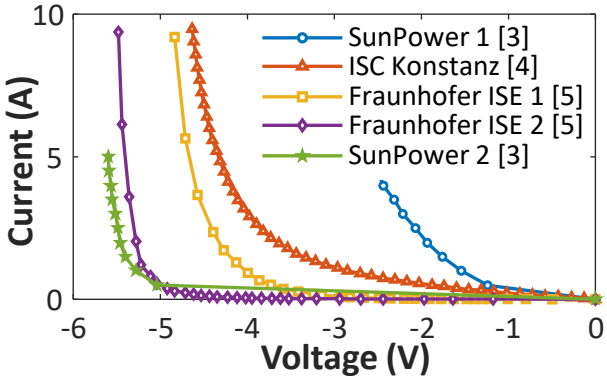
Front/Back Contacted (FBC)





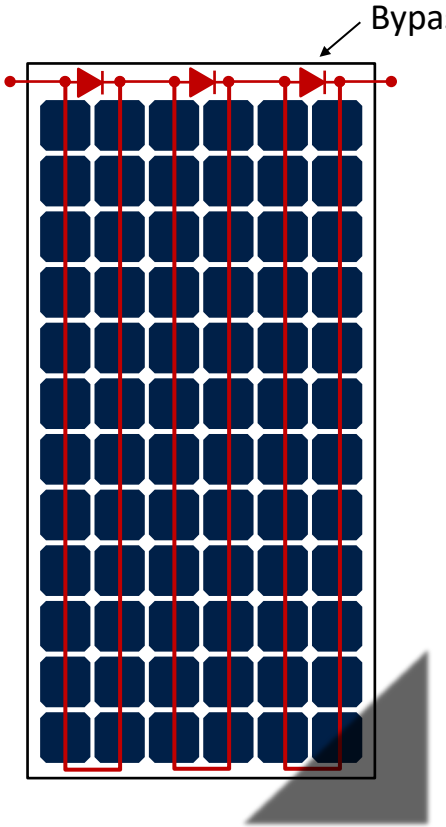
Interdigitated Back Contact (IBC)

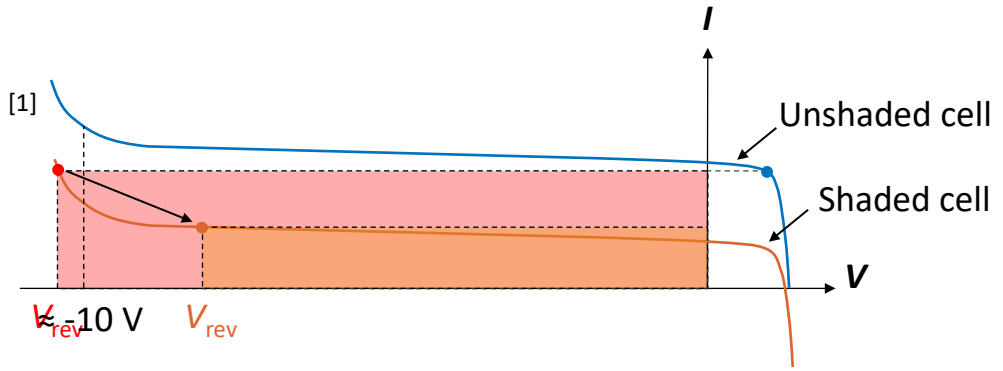




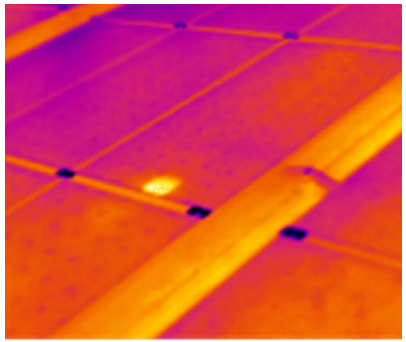
[1] M. A. Green, et al, *Solar Cells* **3**, 233-284 (1981)
[2] K. Chen, et al, *Science China Tech. Sciences* **55**, 594-599 (2012)
[3]D.D. Smith, et al, *IEEE PVSC* **38**, (2012)
[4] H. Chu, et al, *Ener. Proc.* **77**, (2015)
[5] R. Müller, et al, *Sol. Mat.* **142**, (2015)

Partial shading

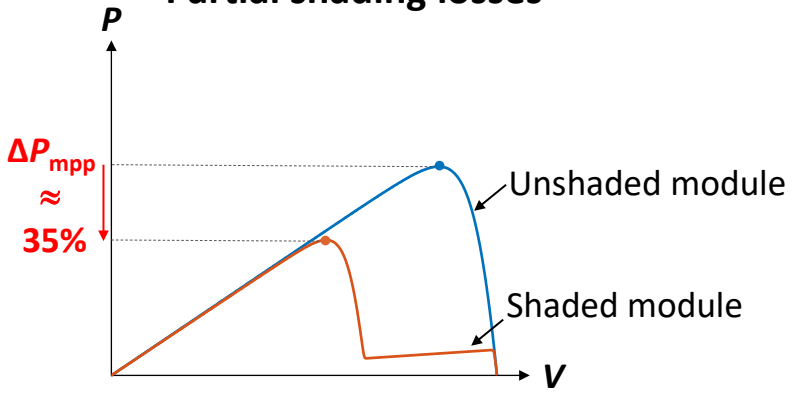




Hot-spots



Partial shading losses



[1] F. Fertig, et al., *Ener Proc* **38**, 32-42 (2013)