WAVE SHAPED WIRES FOR THE INTERCONNECTION OF SILICON SOLAR CELLS WITHOUT BUSBARS OR CONTACT PADS

Li Carlos Rendler, Andreas Beinert,
Andrea Pfreundt, Max Mittag, Achim Kraft

Fraunhofer Institute for Solar Energy Systems ISE

10th Metallization & Interconnection Workshop

Genk, Belgium, 16.11.2021

www.ise.fraunhofer.de

Fraunhofer ISE

AGENDA

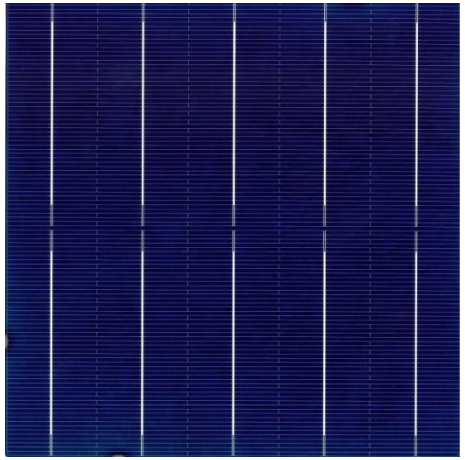
- Contact metallization layouts and interconnection
- Thermomechanical stress after the interconnection of solar cells
- Wave-shaped wires
- Cell-to-Module (CTM) ratio

Fraunhofer ISE

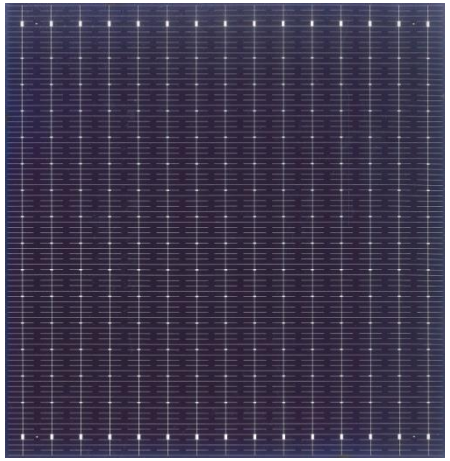
Contact metallization layouts and interconnection

Advantages of wire-based concepts

- Improved efficiency [1, 2]
  - Optical, effective width (EW) of round wires: 0.6 vs. 0.9
  - Shorter current paths [3]
- Lower costs
  - Up to 50% reduce silver consumption (front side) [1, 2]
- Improved Reliability
  - Contact redundancy



5BB



MBB15
(pad rows, no busbars)

0BB
(no pads or busbars)

BB = Busbar(s)
MBB = Multi Busbar

[1] Braun *et al.*, Energy Procedia, vol. 27, pp. 227–233, 2012, DOI: 10.1016/j.egypro.2012.07.056
[2] Braun *et al.*, Energy Procedia, vol. 38, pp. 334–339, 2013, DOI: 10.1016/j.egypro.2013.07.286
[3] Walter *et al.*, Energy Procedia, vol. 55, pp. 380–388, 2014, DOI: 10.1016/j.egypro.2014.08.109

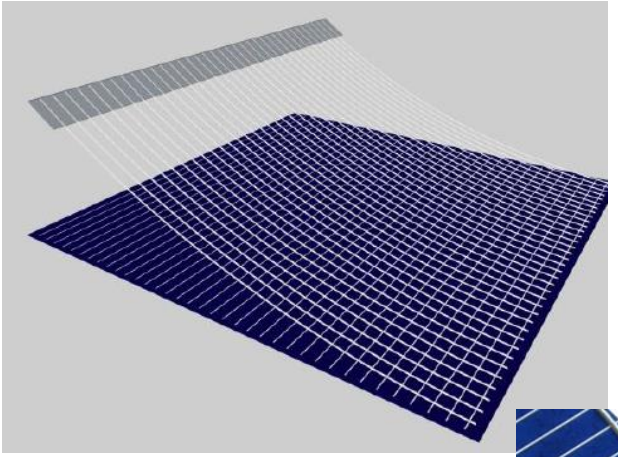
Fraunhofer ISE

Contact metallization layouts and interconnection

Interconnection of 0BB solar cells

- Wire-based technologies
  - Smart Wire Connection Techn. (SWCT) [4]
  - Woven fabric (Polymer- and Cu-wires) [5]

- Electrically conductive adhesives (ECA) [6]



0BB + SWCT

0BB + ECA

[4] Söderström *et al.*, Proc. of the 28th EUPVSEC, 2013, pp. 495–499, DOI: 10.4229/28thEUPVSEC2013-1CV.2.17
[5] Borgers *et al.*, Progress in Photovoltaics, vol. 25, pp. 569–582, 2017, DOI: 10.1002/pip.2851
[6] Geipel *et al.*, Energy Procedia, vol. 55, pp. 336–341, 2014, DOI: 10.1016/j.egypro.2014.08.098

Fraunhofer ISE

Contact metallization layouts and interconnection

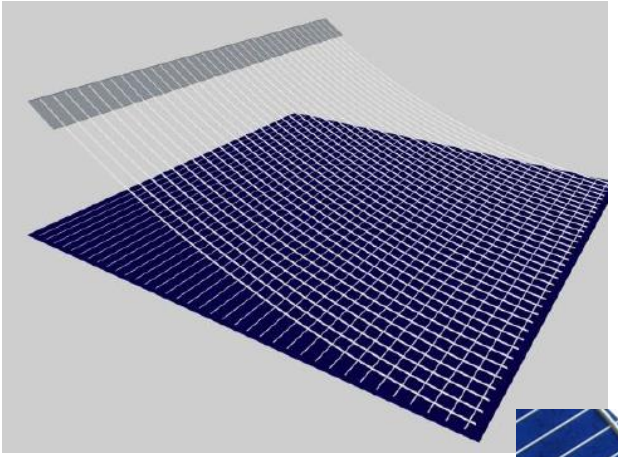
Interconnection of 0BB solar cells

- Wire-based technologies
  - Smart Wire Connection Techn. (SWCT) [4]
  - Woven fabric (Polymer- and Cu-wires) [5]

- Electrically conductive adhesives (ECA) [6]

  → Approx. **higher costs** due to specific materials, like additional polymers, low-temperature solder alloys, or ECA

- **Wave-shaped wires as an alternative concept** using standard solder alloy and no additional polymer material?



0BB + SWCT

0BB + ECA

[4] Söderström *et al.*, Proc. of the 28th EUPVSEC, 2013, pp. 495–499, DOI: 10.4229/28thEUPVSEC2013-1CV.2.17
[5] Borgers *et al.*, Progress in Photovoltaics, vol. 25, pp. 569–582, 2017, DOI: 10.1002/pip.2851
[6] Geipel *et al.*, Energy Procedia, vol. 55, pp. 336–341, 2014, DOI: 10.1016/j.egypro.2014.08.098

Fraunhofer ISE

Thermomechanical stress after the interconnection of solar cells

Why?

- Mismatch of coefficients of thermal expansion (CTEs @ 25 °C)
  - Silicon: 2.6×10^{-6} K^{-1} [7]
  - Copper: 17.0×10^{-6} K^{-1} [8]

→ 6.5 times larger CTE of Cu causes

→ Deformation (single side)

→ Thermomechanical stress (double side)

Soldering ribbons on busbars (single side)

Illustration of thermal contraction (double side)

[7] Lyon *et al.*, Journal of Applied Physics, vol. 48, pp. 865–868, 1977, DOI: 10.1063/1.323747
[8] Wiese *et al.*, Proc. of the 11th EuroSimE, 2010, pp. 1–5, DOI: 10.1109/esime.2010.5464551

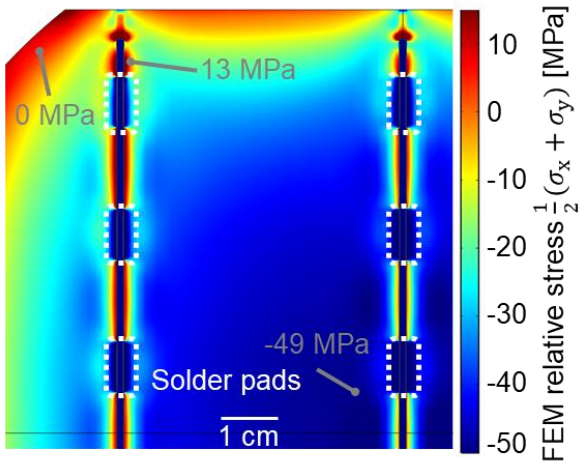
Fraunhofer ISE

Thermomechanical stress after the interconnection of solar cells
Simulation and measurement

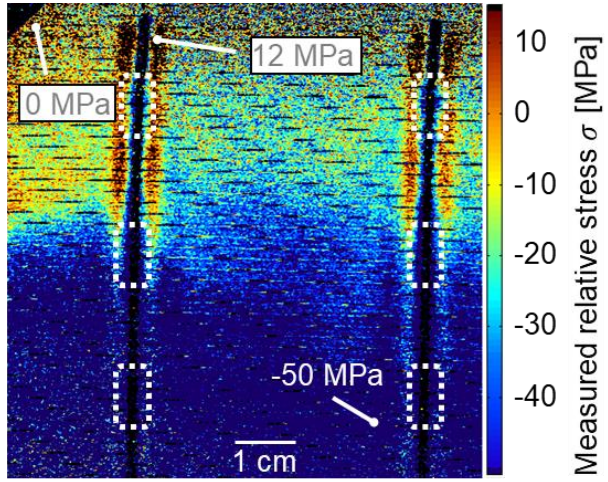
- Determination of the stress distribution
  - FEM simulations [9, 10]
  - Raman measurements [9]

→ Stress maxima near outermost contact (pads or busbars)

- Alternative: Measurement with cell integrated sensors [11]



FEM simulation
(1/4 solar cell)



Raman measurement
(1/4 solar cell)

[9] Beinert *et al.*, SOLMAT, vol. 193, pp. 351–360, 2019, DOI: 10.1016/j.solmat.2019.01.028
[10] Rendler *et al.*, Proc. of the 32nd EUPVSEC, 2016, pp. 94–98. doi: 10.4229/EUPVSEC20162016-1CO.11.2
[11] Beinert *et al.*, Progress in Photovoltaics, vol. 28, pp. 717–724, 2020, DOI: 10.1002/pip.3263

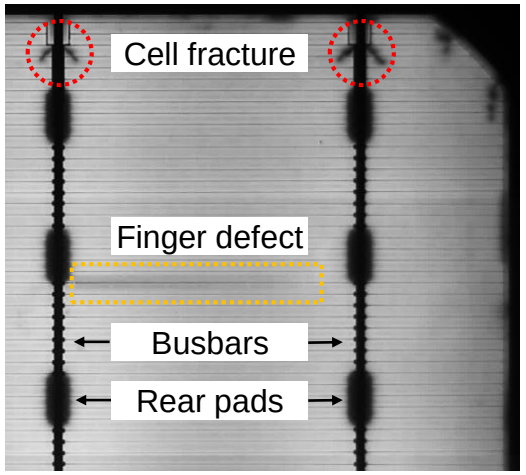
Fraunhofer ISE

Thermomechanical stress after the interconnection of solar cells

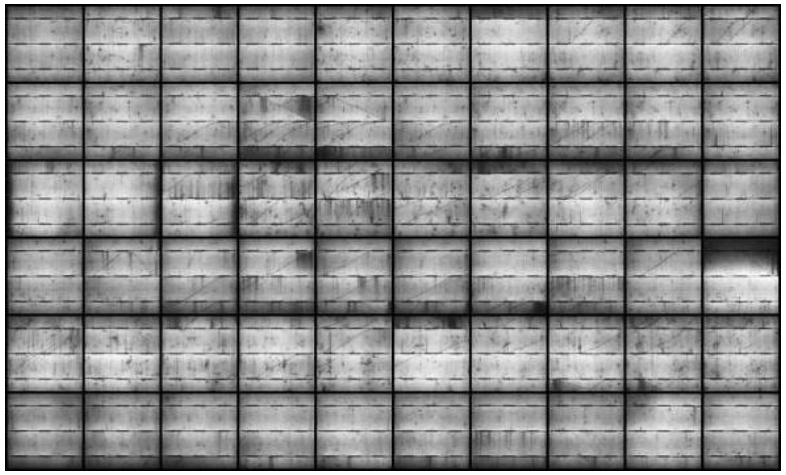
Consequences

- Potential defects
  - Cell fracture
  - Finger defects
  - Interconnection failure

→ Lower efficiency / power of a PV module



EL of solar cell with cracks



EL of PV module with damages

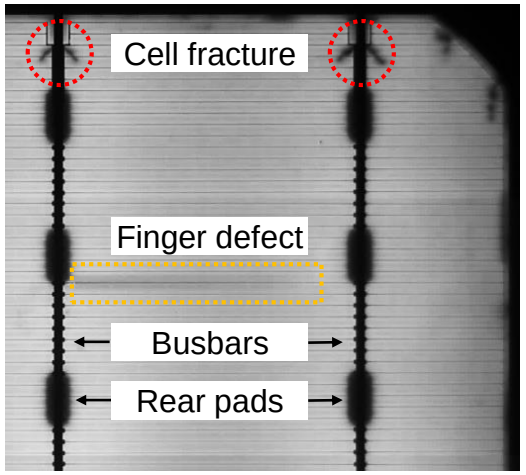
Fraunhofer ISE

Thermomechanical stress after the interconnection of solar cells

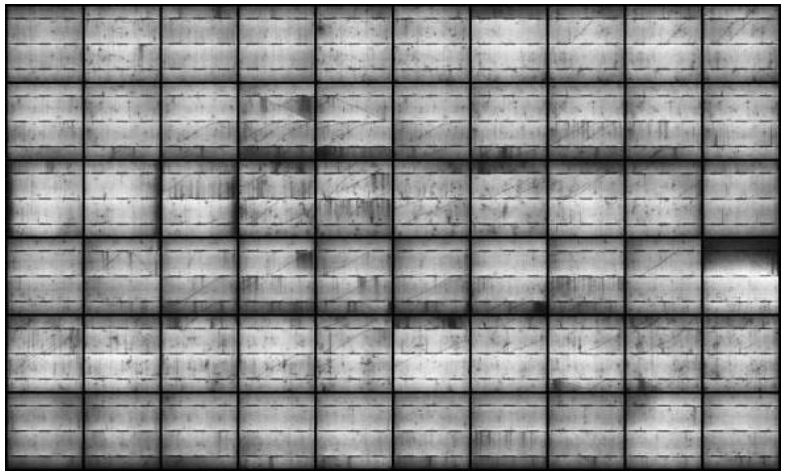
Consequences

- Potential defects
  - Cell fracture
  - Finger defects
  - Interconnection failure

→ Lower efficiency / power of a PV module

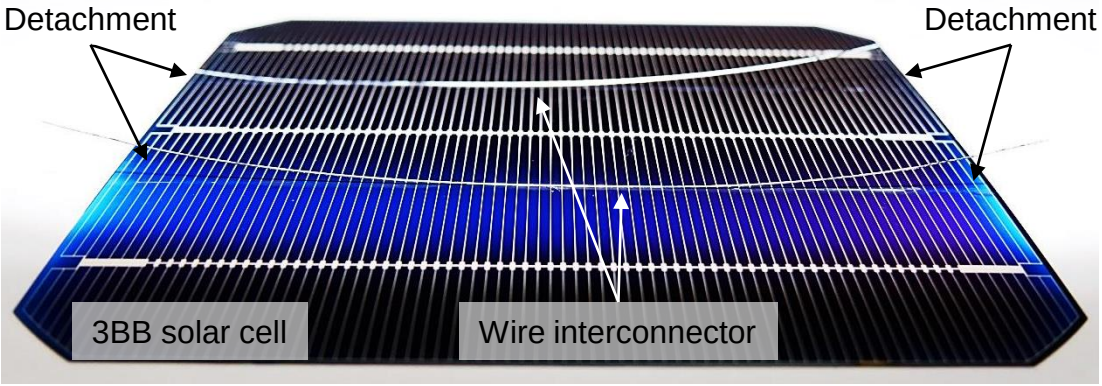


EL of solar cell with cracks



EL of PV module with damages

- Not possible to solder straight wires on 0BB solar cells

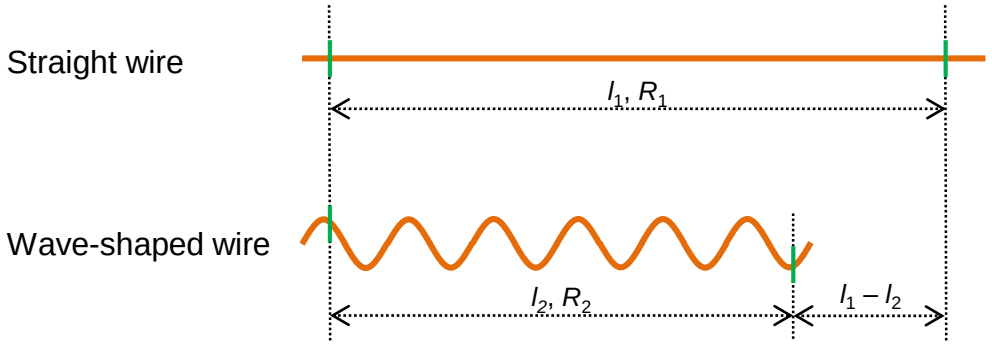


Soldering straight wires on contact finger grid

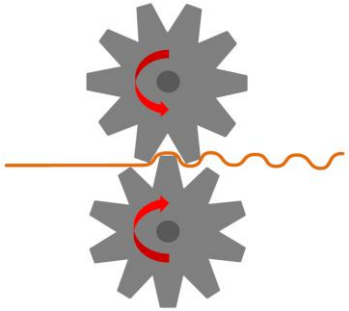
Fraunhofer ISE

Wave-shaped wires
Geometry and method

- Length change
- Mechanical properties?
- Electrical resistance change?



Geometry change for wave-shaping



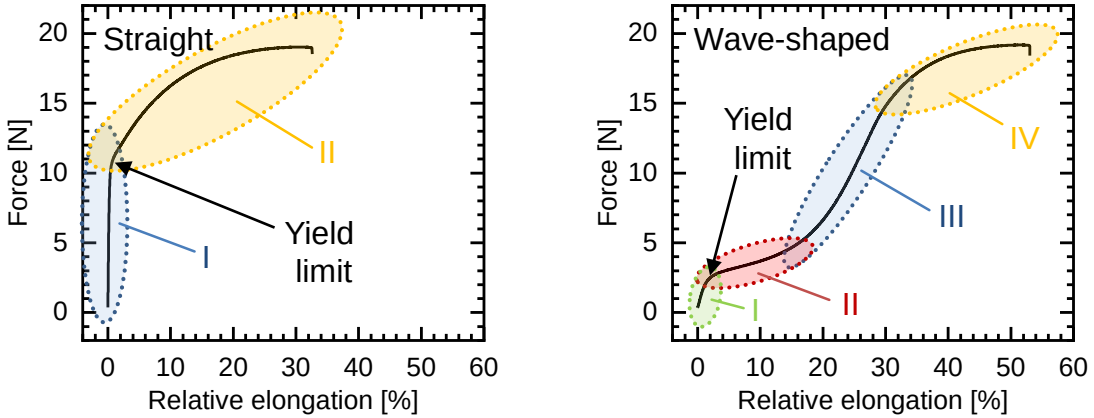
Schematic drawing of wire deformation

Wave-shaped wire example

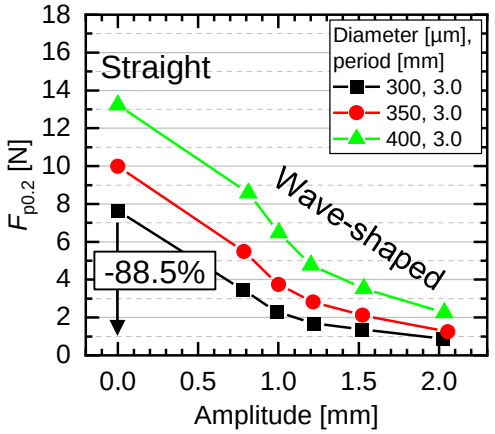
Fraunhofer ISE

Wave-shaped wires
Physical properties

- Mechanical properties [12]
  - Substantial compliance increase



Force-elongation curve

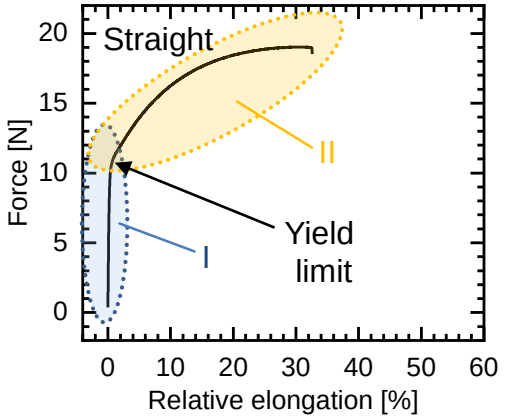


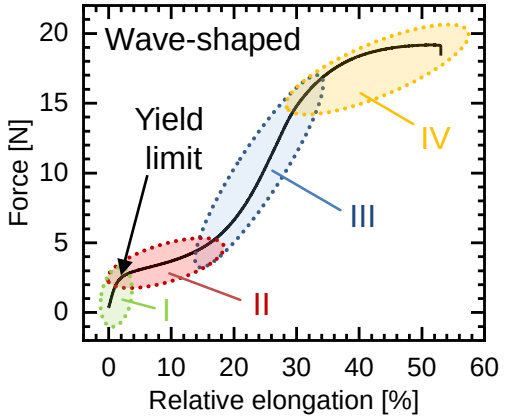
Pseudo yield limit

[12] Rendler *et al.*, SOLMAT, vol. 176, pp. 204–211, 2018. doi: 10.1016/j.solmat.2017.11.022

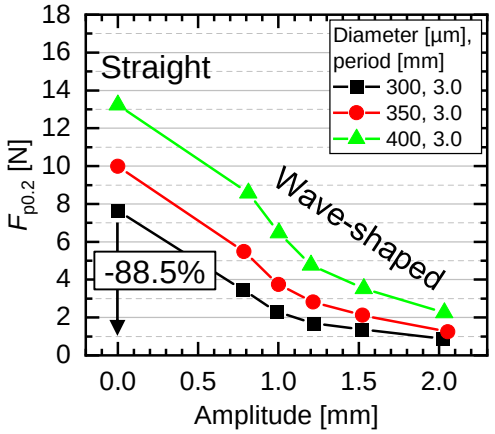
Wave-shaped wires
Physical properties

- Mechanical properties [12]
  - Substantial compliance increase ☑
- Electrical properties [12]
  - Resistance increase ☒

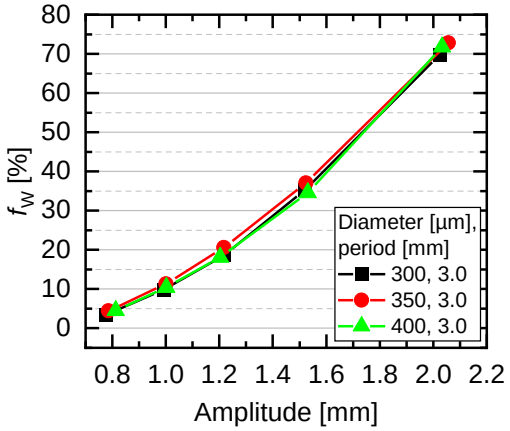




Force-elongation curve



Pseudo yield limit



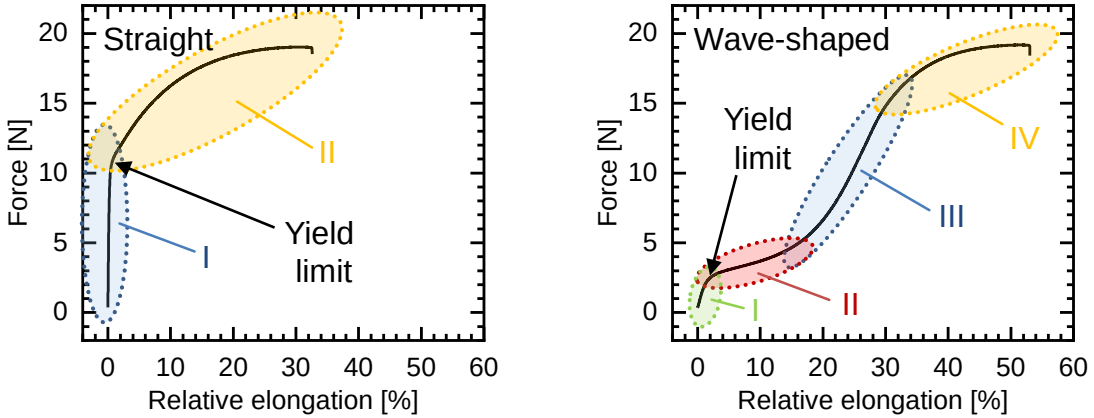
Electrical resistance

[12] Rendler *et al.*, SOLMAT, vol. 176, pp. 204–211, 2018. doi: 10.1016/j.solmat.2017.11.022

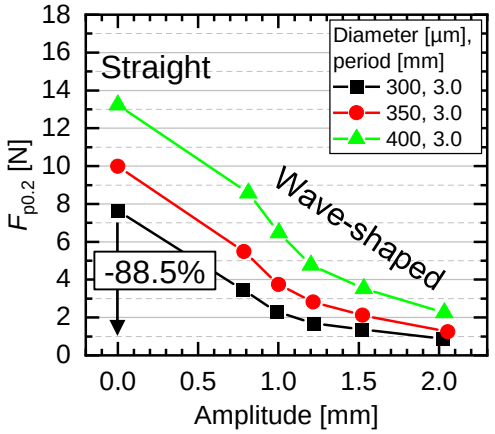
Fraunhofer ISE

Wave-shaped wires
Physical properties

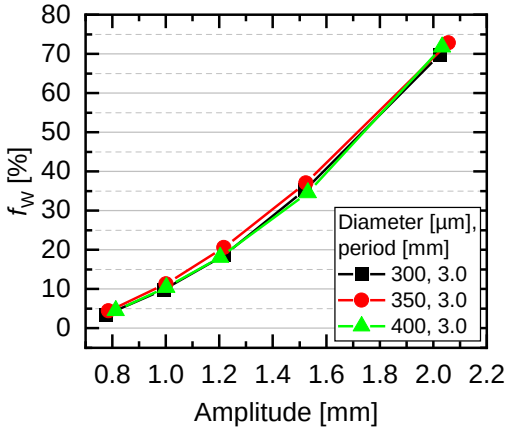
- Mechanical properties [12] ✓
  - Substantial compliance increase
- Electrical properties [12] ✗
  - Resistance increase
- **Solderability and reliability (for 0BB solar cells)?** ?
- **Optical properties and potential performance of a PV module?** ?



Force-elongation curve



Pseudo yield limit



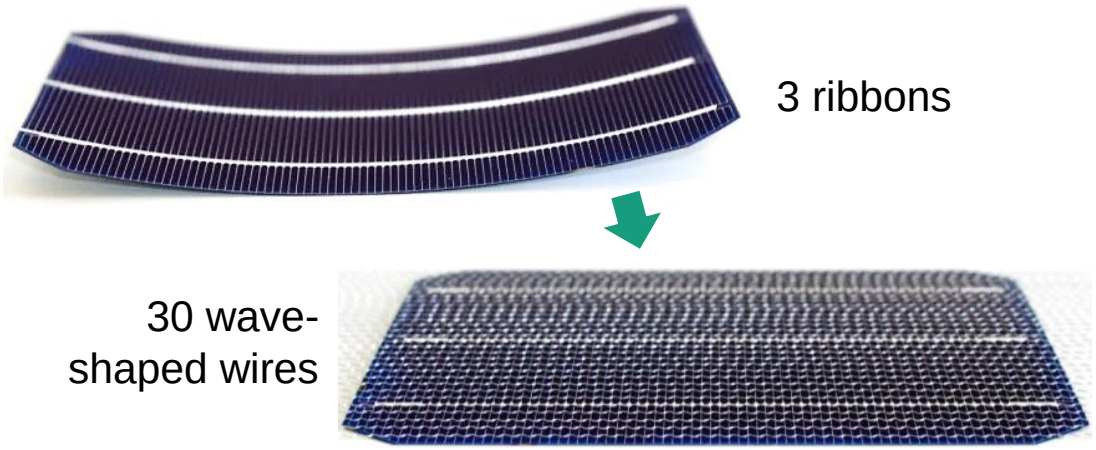
Electrical resistance

[12] Rendler *et al.*, SOLMAT, vol. 176, pp. 204–211, 2018. doi: 10.1016/j.solmat.2017.11.022

Fraunhofer ISE

Wave-shaped wires
Interconnection [13, 14]

- Semi automatic soldering process
  - Hotplate + IR lamp
- Comparison of solar cell deformation (single side soldering)
  - Minimized deformation

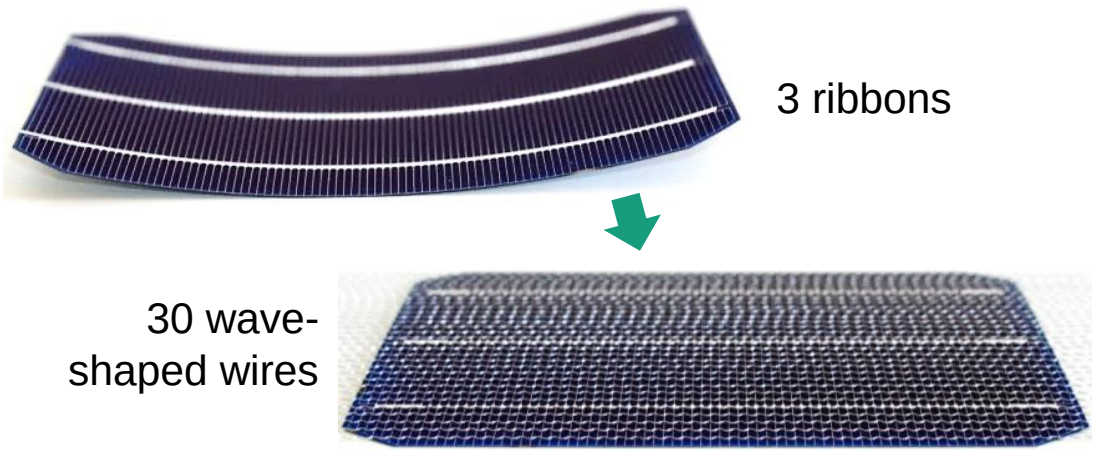


Comparison of solar cell deformation

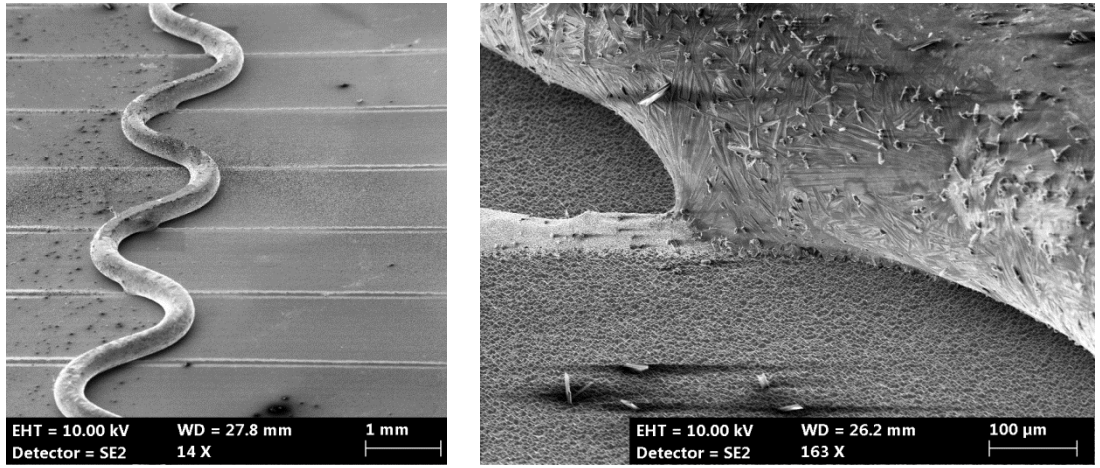
[13] Rendler *et al.*, Energy Procedia, vol. 124, pp. 478–483, 2017, DOI: 10.1016/j.egypro.2017.09.284
[14] Rendler *et al.*, AIP Conf. Proc., vol. 1999, pp. 080001-1–080001-8, 2018, DOI: 10.1063/1.5049303

Wave-shaped wires
Interconnection [13, 14]

- Semi automatic soldering process
  - Hotplate + IR lamp
- Comparison of solar cell deformation (single side soldering)
  - Minimized deformation ☑
- Scanning electron microscopy (SEM)
  - Wetting of contact fingers ☑



Comparison of solar cell deformation



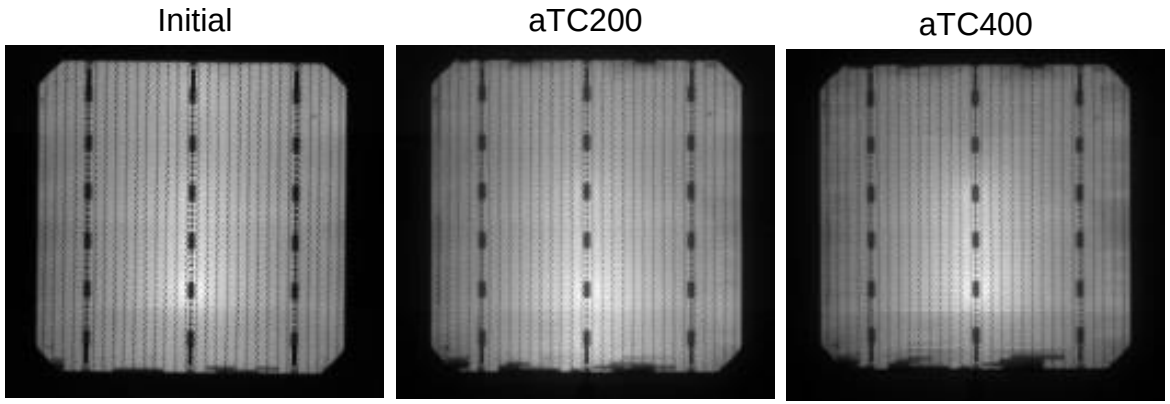
SEM images of wave-shaped wire on finger grid

[13] Rendler *et al.*, Energy Procedia, vol. 124, pp. 478–483, 2017, DOI: 10.1016/j.egypro.2017.09.284
[14] Rendler *et al.*, AIP Conf. Proc., vol. 1999, pp. 080001-1–080001-8, 2018, DOI: 10.1063/1.5049303

Fraunhofer ISE

Wave-shaped wires
Reliability [13, 14]

- One-cell modules with full and half solar cells
- Thermal cycling (up to 400 cycles)
  - EL imaging: Few finger defects

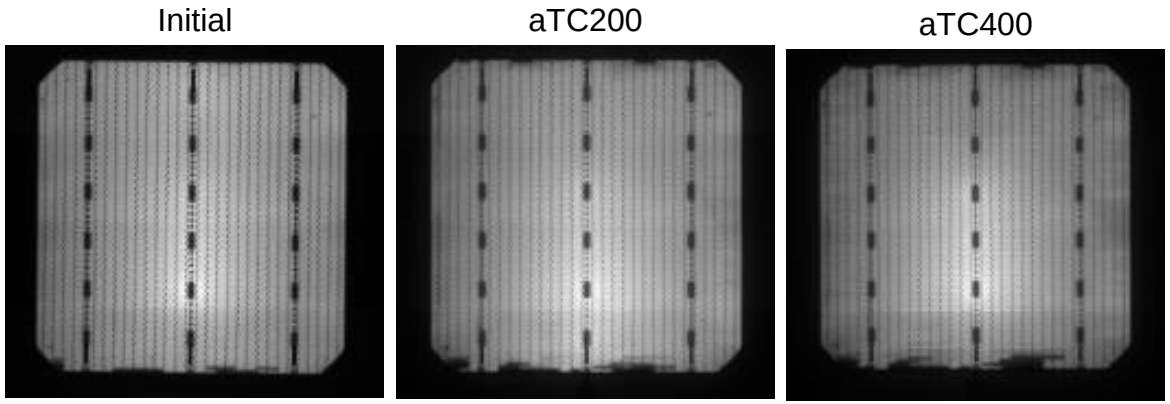


EL images after thermal cycling

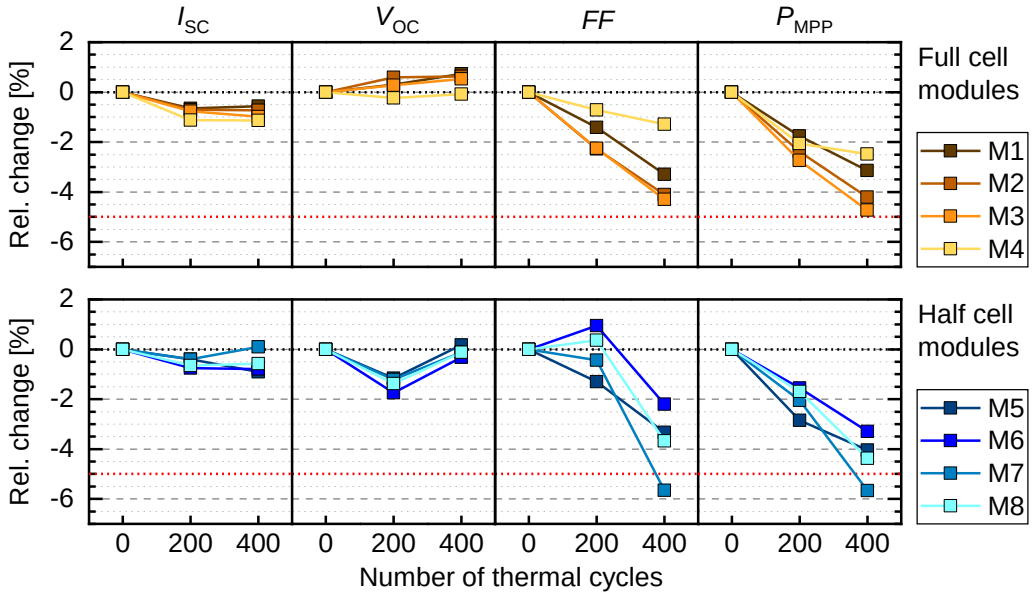
[13] Rendler *et al.*, Energy Procedia, vol. 124, pp. 478–483, 2017, DOI: 10.1016/j.egypro.2017.09.284
[14] Rendler *et al.*, AIP Conf. Proc., vol. 1999, pp. 080001-1–080001-8, 2018, DOI: 10.1063/1.5049303

Wave-shaped wires
Reliability [13, 14]

- One-cell modules with full and half solar cells
- Thermal cycling (up to 400 cycles)
  - EL imaging: Few finger defects
  - IV measurements: 7 of 8 samples with < 5% power degradation



EL images after thermal cycling



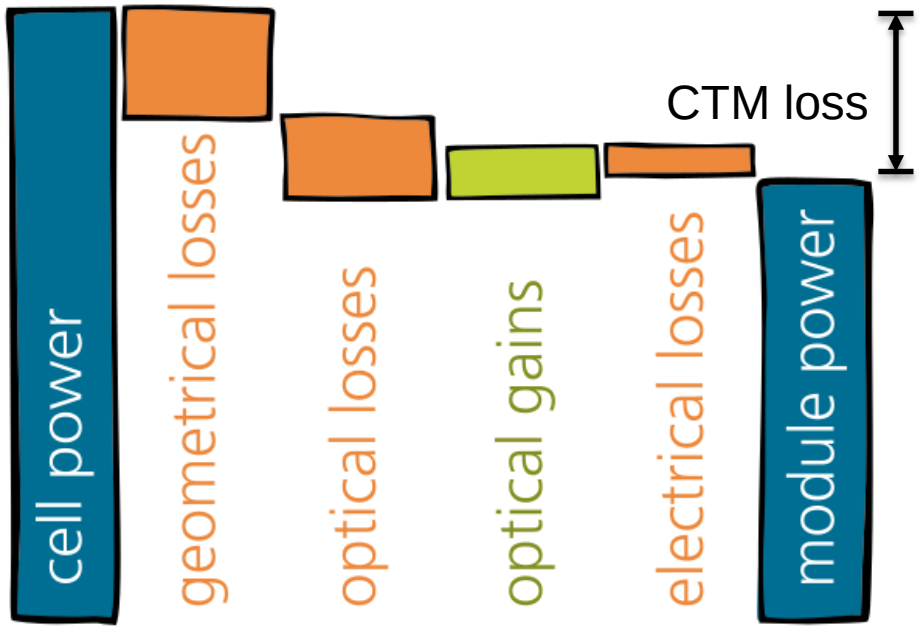
Results of IV measurement after thermal cycling

[13] Rendler *et al.*, Energy Procedia, vol. 124, pp. 478–483, 2017, DOI: 10.1016/j.egypro.2017.09.284
[14] Rendler *et al.*, AIP Conf. Proc., vol. 1999, pp. 080001-1–080001-8, 2018, DOI: 10.1063/1.5049303

Fraunhofer ISE

Cell-to-Module (CTM) ratio
Motivation

- What's the CTM ratio? [15, 16]
  - Module power ≠ cell power
  - Module efficiency ≠ cell efficiency
    - Measurement of 0BB complex [17]
- Power loss = cost factor!
  - Solar cells are bought at $/Wp
  - Modules are sold at $/Wp



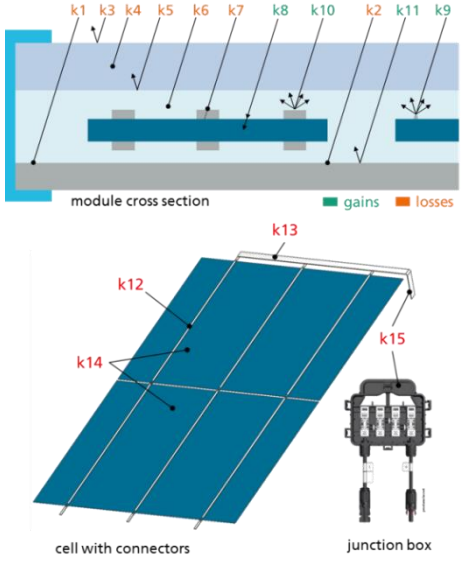
What influences the power/efficiency of a PV module?

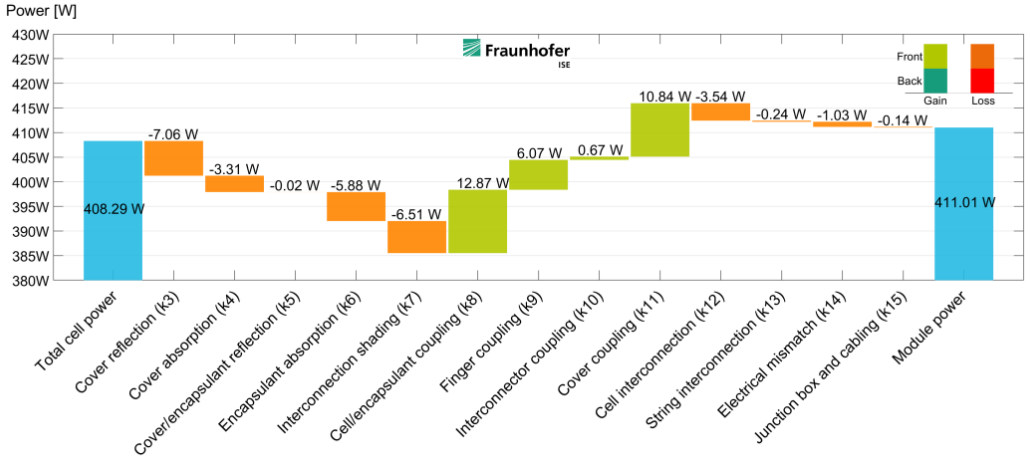
[15] Hädrich *et al.*, SOLMAT, vol. 131, pp. 14–23, 2014. doi: 10.1016/j.solmat.2014.06.025
[16] Mittag *et al.*, Photovoltaics International, vol. 36, pp. 97–104, 2017
[17] Rauer *et al.*, Photovoltaics International, vol. 45, pp. 53–62, 2020

Fraunhofer ISE

Cell-to-Module (CTM) ratio
Calculation by SmartCalc.CTM

- Detailed understanding and scientific modelling of gains and losses by user-friendly software interface allows access to flexible and precise analysis [15, 16]





SmartCalc.CTM
www.cell-to-module.com

CTM analysis by SmartCalc.CTM (Free version available online)

[15] Hädrich *et al.*, SOLMAT, vol. 131, pp. 14–23, 2014. doi: 10.1016/j.solmat.2014.06.025
[16] Mittag *et al.*, Photovoltaics International, vol. 36, pp. 97–104, 2017

Fraunhofer ISE

Cell-to-Module (CTM) ratio
Assumptions and analysis

- Six different solar cells (156.75 x 156.75 mm², half and full solar cells)
  - **5BB, MBB12, and 0BB**

  → MBB and 0BB solar cell parameters calculated by adjustment of the IV-curve

- Three interconnection technologies
  - 5BB → Flat ribbons (0.9 x 0.22 mm², EW: 0.9)
  - MBB12 → Straight, round wires (350 µm, EW: 0.6)
  - 0BB → Wave-shaped, round wires (Variations: number, diameter, amplitude)

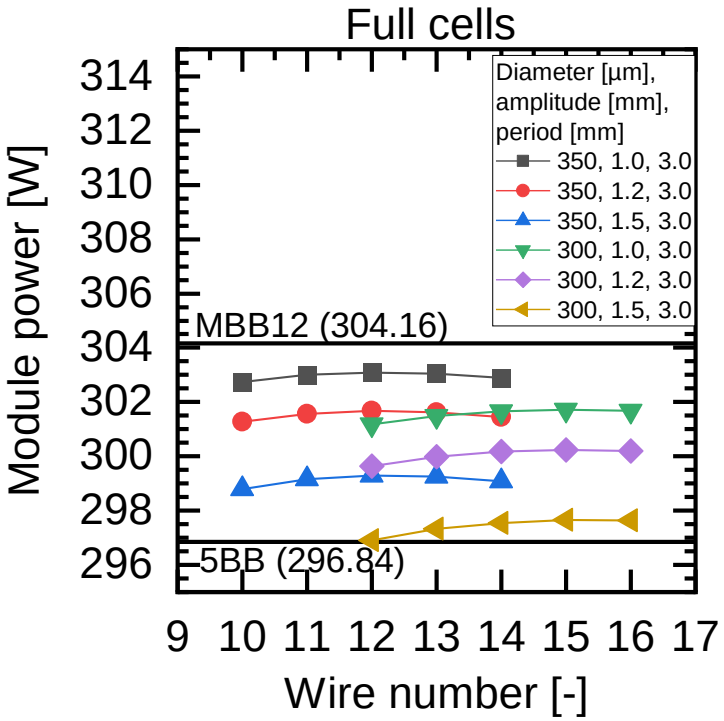
- **Potential PV module power?**

Fraunhofer ISE

Cell-to-Module (CTM) ratio

Results of the power calculation

- **Full solar cells (60-cell module)**
  - 5BB → 296.8 W (95%)
  - MBB12 → 304.2 W (97%)
  - 0BB → 296.9 - 303.1 W (94% - 96%)



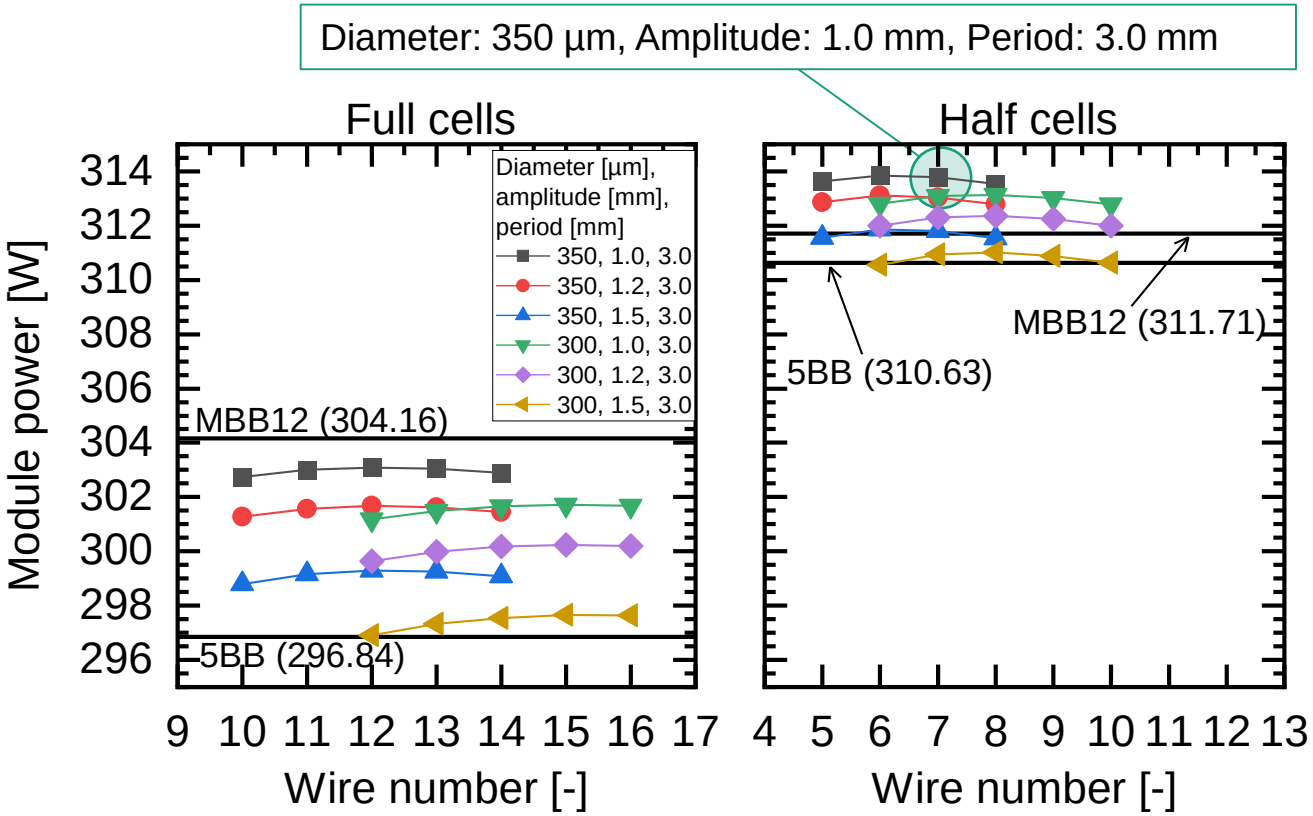
Power results for a PV module

Fraunhofer ISE

Cell-to-Module (CTM) ratio

Results of the power calculation

- **Full solar cells (60-cell module)**
  - 5BB → 296.8 W (95%)
  - MBB12 → 304.2 W (97%)
  - 0BB → 296.9 - 303.1 W (94% - 96%)
- **Half solar cells (120-cell module)**
  - 5BB → 310.6 W (100%)
  - MBB12 → 311.7 W (100%)
  - 0BB → 310.6 - 313.9 W (98% - 99%) ✓

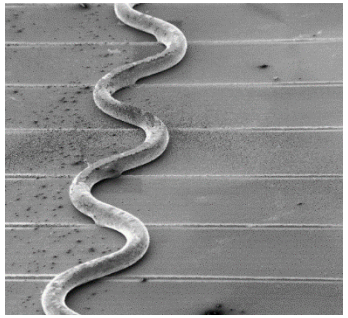


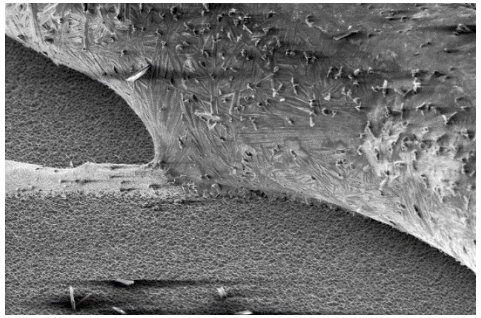
Power results for a PV module

- **Potential of power increase for 0BB solar cells and wave-shaped wires demonstrated**

Fraunhofer ISE

Summary

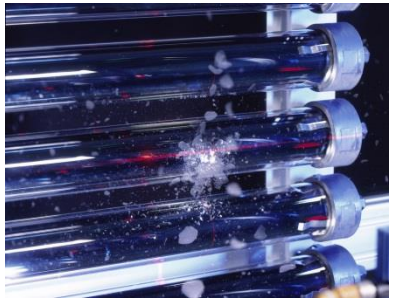
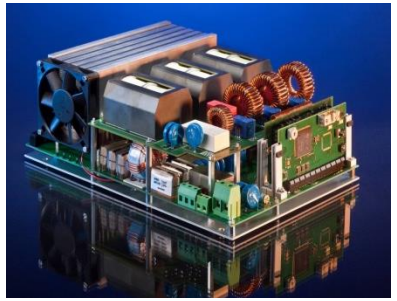
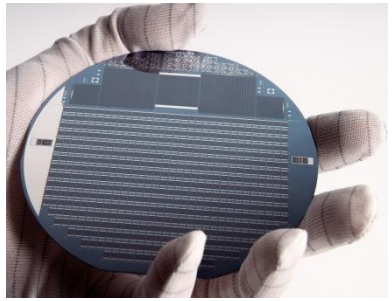




- Substantial compliance increase for wave-shaped wires → **Up to 88.5% yield limit reduction**
- Reliable interconnection of solar cells without pads or busbars by soldering of wave shaped wires on the finger grid demonstrated → **Less than 5% power degradation after 400 thermal cycles**
- Power of PV module with half and full solar cells and three different interconnection concepts calculated by SmartCalc.CTM → **Power increase with wave-shaped wires on half solar cells**
- Outlook
  - Tailored metallization designs for improved edge contacts
  - Non-continuous wave-shaping for increased power / efficiency and reliable interconnection

Thank you for your Attention!




Fraunhofer Institute for Solar Energy Systems ISE

Li Carlos Rendler, Andreas Beinert, Andrea Pfreundt, Max Mittag, Achim Kraft

www.ise.fraunhofer.de