Project “FEUERDRACHE“: Process Development and Control of Contact Firing Processes for High-Efficiency Silicon Solar Cells

G. Emanuel[1], D. Ourinson[1], G. Dammaß[2],
H. Müller[3], C. Sternkiker[4], F. Ogiewa[5],
K. Rahmanpour[1], T. Javaid[1], A. Csordás[1], S. Nold[1],
S. W. Glunz[1], F. Clement[1]

9th Metallization & Interconnection Workshop

Online Conference, 05.10.2020

www.ise.fraunhofer.de

5 TRUMPF 4 Heraeus 3 rehm THERMAL SYSTEMS 2 INFRATEC. 1 Fraunhofer ISE

Project “Feuerdrache”
General Information

- Feuerdrache:
  “Process Development and Control of Contact Firing Processes for High-efficiency Si Solar Cells”
- Funding period: 01.07. 2017 – 30.06. 2020
- Four partners involved
  - InfraTec
  - Rehm Thermal Systems
  - Heraeus Noblelight
  - Trumpf Photonic Components (former Philips Photonics)
- Partners main expertise
  - (IR) camera systems
  - Fast-Firing equipment
  - Conventional heating lamps and alternatives
  - Laser system for wafer heating

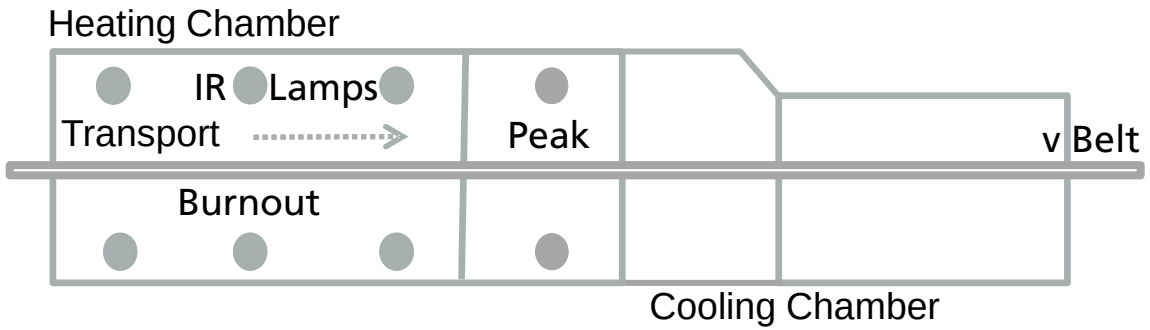
Motivation and Aims

Improving Firing Process and Evaluating Alternative Technologies

- Project motivation:
  - Improvement of process and technology of industrial firing process
  - Higher flexibility in adaption of firing profiles with extended firing furnace
  - No inline capable quality assurance

FF-Plus furnace at Fh-ISE PVTEC

Firing Furnace by *Rehm Thermal Systems*



Cross-section scheme of industrial furnace

Fraunhofer ISE

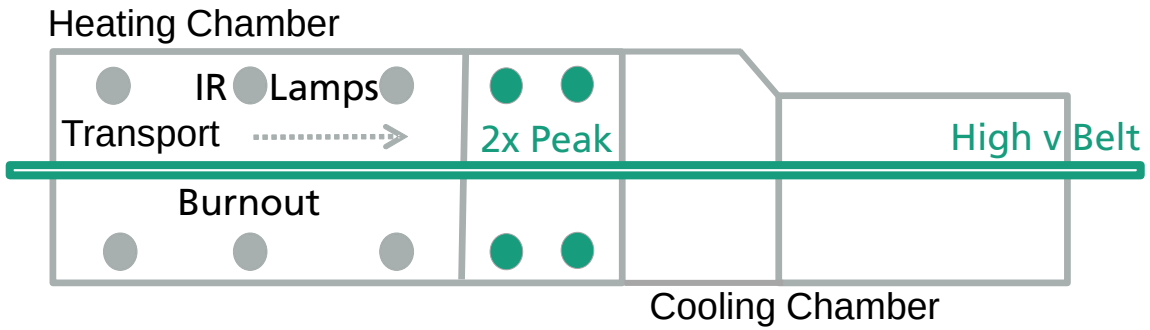
Motivation and Aims

Improving Firing Process and Evaluating Alternative Technologies

- Project motivation:
  - Improvement of process and technology of industrial firing process
  - Higher flexibility in adaption of firing profiles with extended firing furnace
  - No inline capable quality assurance
- Project aims
  1. Higher throughput for industrial production

FF-Plus furnace at Fh-ISE PVTEC

Firing Furnace by *Rehm Thermal Systems*



Cross-section scheme
(in green changes to industry)

Fraunhofer ISE

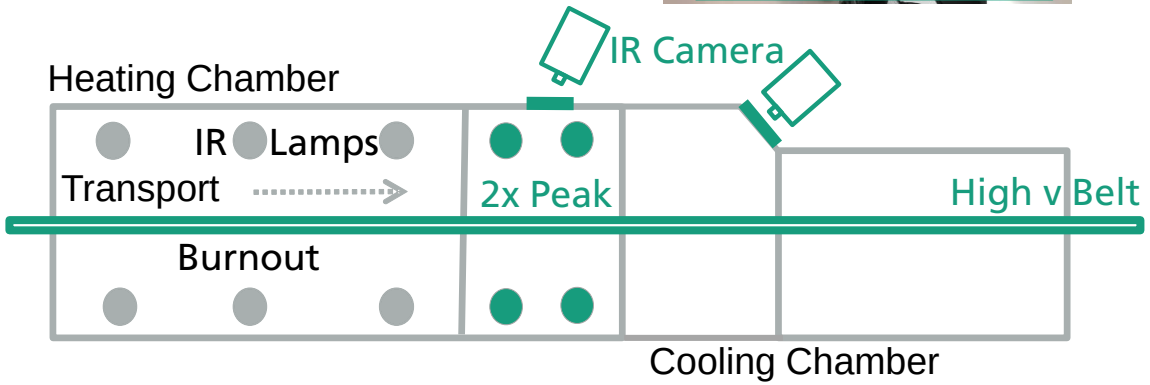
Motivation and Aims

Improving Firing Process and Evaluating Alternative Technologies

- Project motivation:
  - Improvement of process and technology of industrial firing process
  - Higher flexibility in adaption of firing profiles with extended firing furnace
  - No inline capable quality assurance
- Project aims
  1. Higher throughput for industrial production
  2. Integration of IR camera for process control

FF-Plus furnace at Fh-ISE PVTEC

Firing Furnace by *Rehm Thermal Systems*



Cross-section scheme
(in green changes to industry)

Fraunhofer ISE

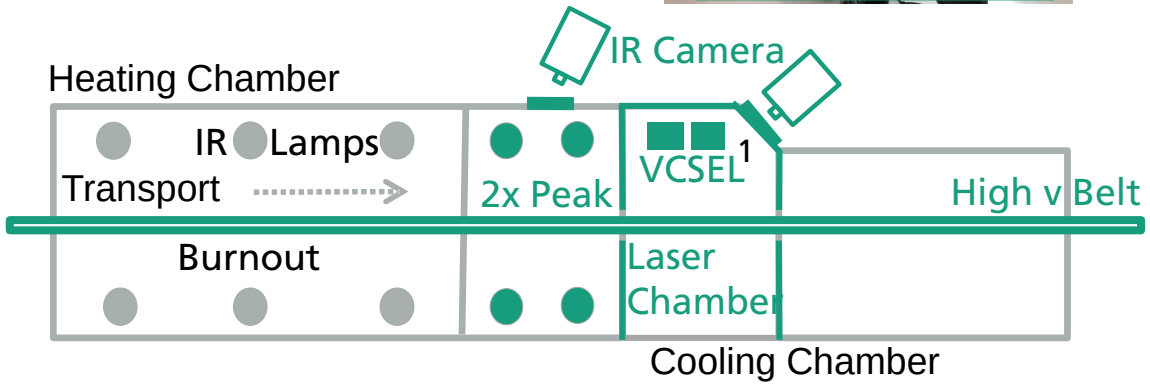
Motivation and Aims

Improving Firing Process and Evaluating Alternative Technologies

- Project motivation:
  - Improvement of process and technology of industrial firing process
  - Higher flexibility in adaption of firing profiles with extended firing furnace
  - No inline capable quality assurance
- Project aims
  1. Higher throughput for industrial production
  2. Integration of IR camera for process control
  3. Evaluation of alternative Laser Firing Technology

FF-Plus furnace at Fh-ISE PVTEC

Firing Furnace by *Rehm Thermal Systems*



Cross-section scheme
(in green changes to industry)

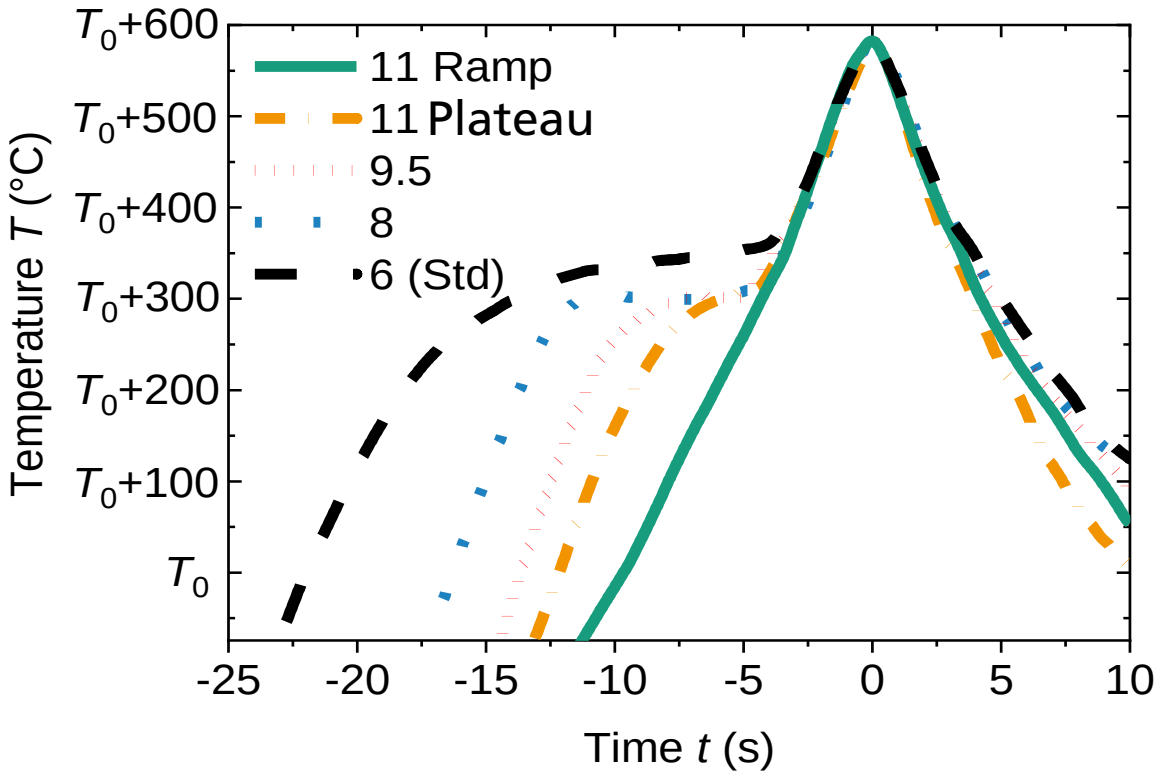
[1]VCSEL - vertical cavity emitting surface laser

Higher Belt Velocity
Firing Profiles

1. Higher throughput for industrial production
2. Integration of IR camera for process control
3. Evaluation of alternative Laser Firing Technology

Measurements taken by thermocouples on PERC solar cells

- Variation in the belt velocity upto nearly double speed
- Maintaining the peak shape and the cooling ramp
- Adaption of burnout profiles[1,2]
  - From shorter plateau up to „ramp“
- Ramp for „High-speed“ processes



Time-temperature profiles via thermocouple measurements for the belt speed variation

[1]D. Ourinson et al., SiPV, 2019

[2]D. Ourinson et al., AIP, 2019

Fraunhofer ISE

Higher Belt Velocity
PERC Cell Results

Experiment

- Comparison of PERC solar cells with standard process flow
- Using adapted firing profiles with high velocity

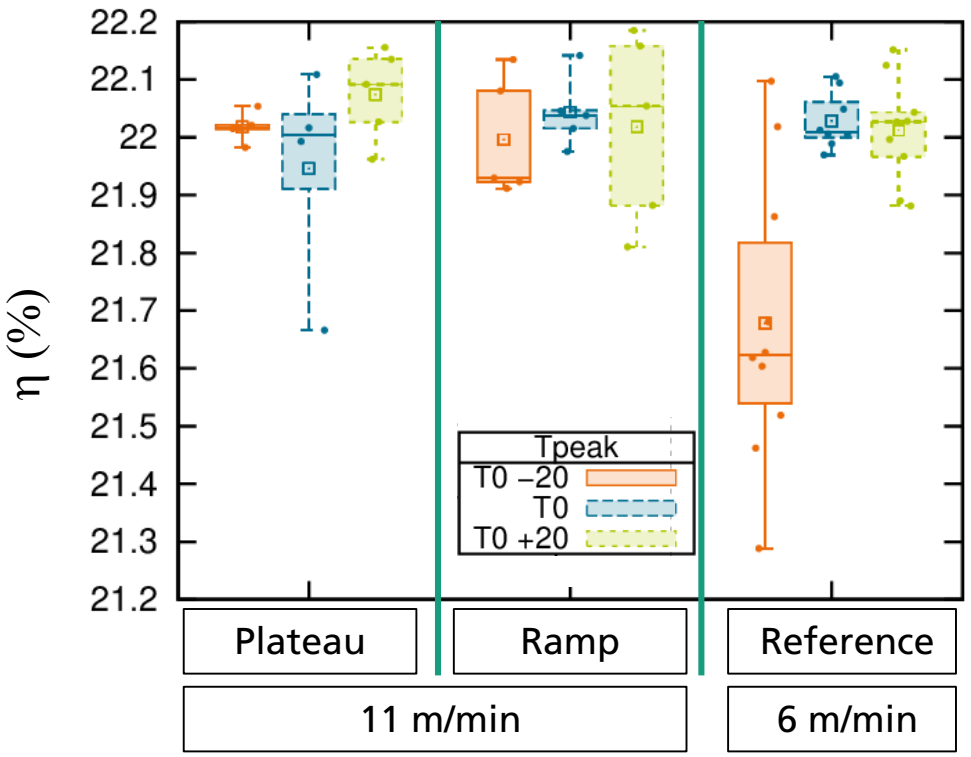
Higher Belt Velocity
PERC Cell Results

Experiment

- Comparison of PERC solar cells with standard process flow
- Using adapted firing profiles with high velocity

Results

- Efficiency compared to the standard process identical
- No difference in series resistance



Efficiency of PERC cells. Variation in peak firing profiles and temperature

Fraunhofer ISE

Higher Belt Velocity
PERC Cell Results

Experiment

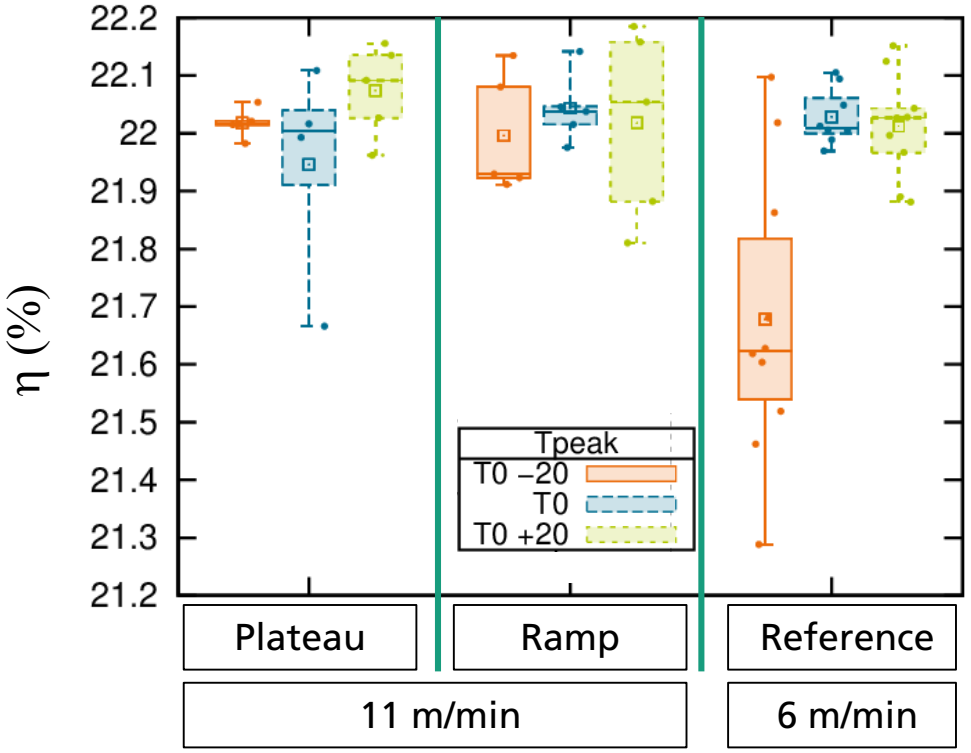
- Comparison of PERC solar cells with standard process flow
- Using adapted firing profiles with high velocity

Results

- Efficiency compared to the standard process identical
- No difference in series resistance
- Proof of interconnection and module fabrication

→ Higher throughput with fast belt velocity possible

Module produced with industrial stringer



Efficiency of PERC cells. Variation in peak firing profiles and temperature

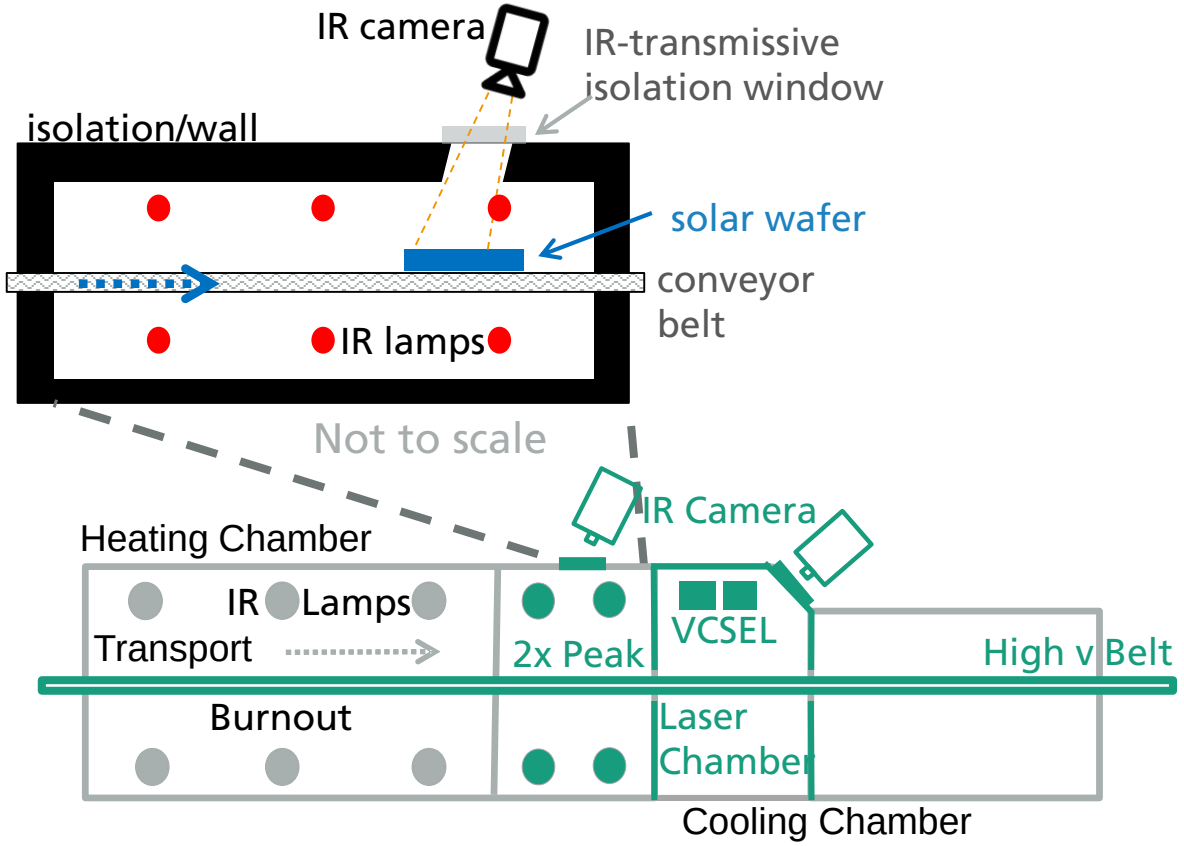
Fraunhofer ISE

Inline Wafer Temperature Measurements
Setup and Integration of IR Camera System

1. Higher throughput for industrial production
2. Integration of IR camera for process control
3. Evaluation of alternative Laser Firing Technology

Adaption of fast firing furnace

- Realisation of optical path
  - At the end of the peak zone for the conventional furnace[1-3]
  - In the laser chamber to visualized the laser process area
- Realisation of two different transmissive windows (optical path and laser protection)
- No changes in profile after creation of optical path



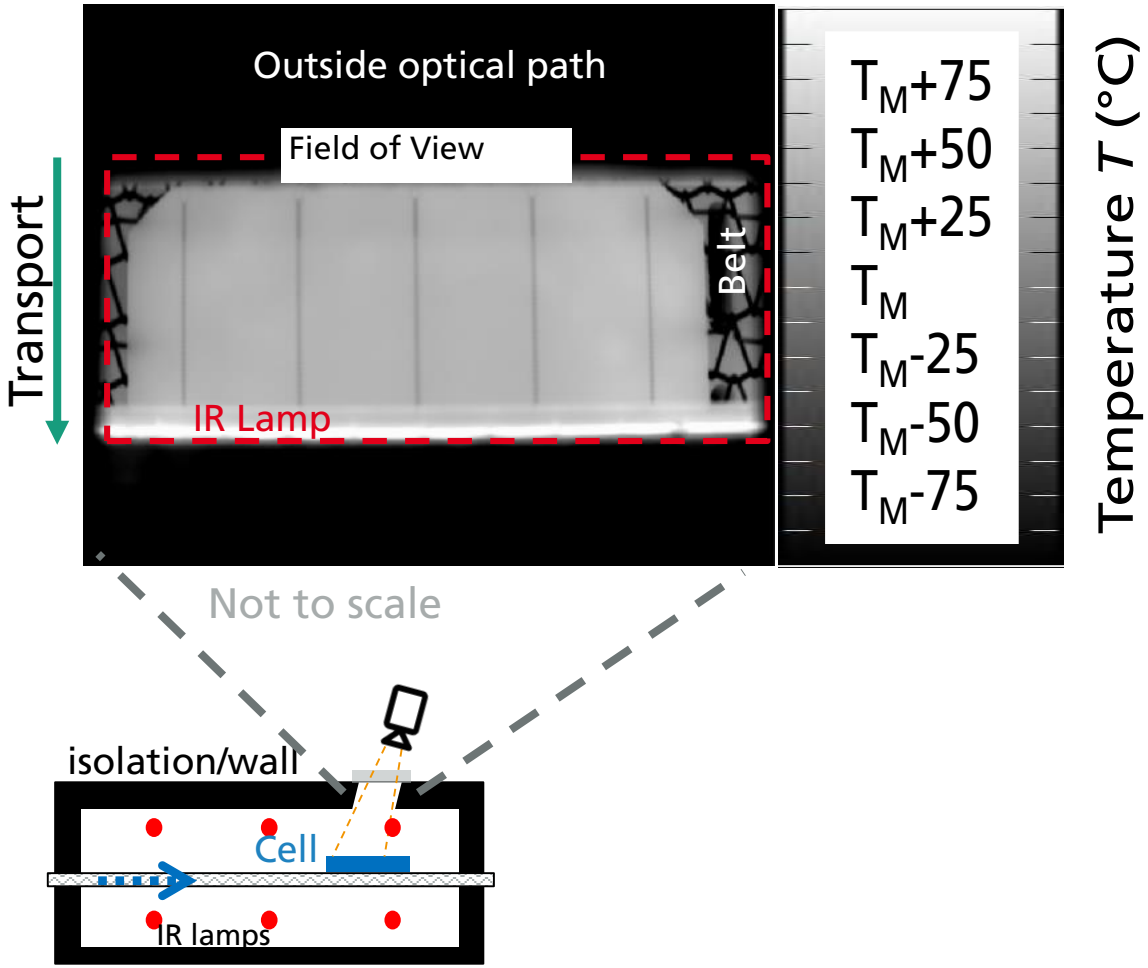
[1]D. Ourinson et al., PSS-RRL, 2019
[2]D. Ourinson et al., Metallization Workshop, 2019
[3]D. Ourinson et al., JoVE, 2020

Fraunhofer ISE

Inline Wafer Temperature Measurements
Temperature Analysis

Inline Measurements of Wafer Temperature

- Calibration for both setups realized
- Snapshot of the trailing part of a heated-up wafer passing the area of the peak temperature in the furnace peak zone



Fraunhofer ISE

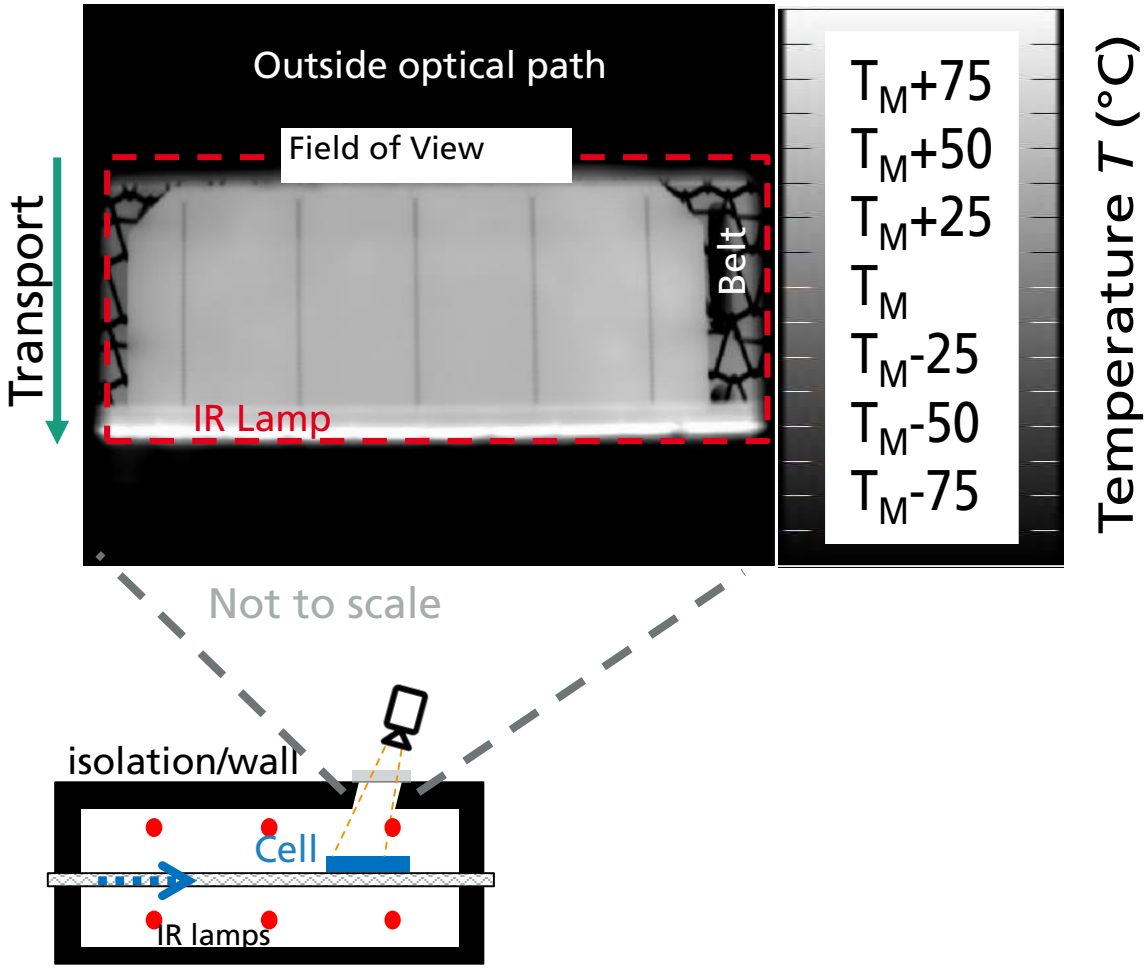
Inline Wafer Temperature Measurements
Temperature Analysis

Inline Measurements of Wafer Temperature

- Calibration for both setups realized
- Snapshot of the trailing part of a heated-up wafer passing the area of the peak temperature in the furnace peak zone

Advantages

- Quality assurance of each wafer possible
- No interruption of production
- On the fly adaption of peak temperature possible

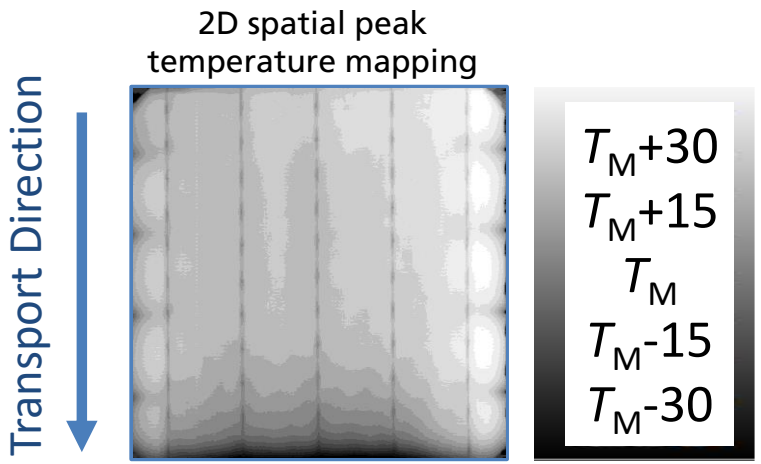


Fraunhofer ISE

Inline Wafer Temperature Measurements

Measurement Results with the IR Camera System

- Spatially resolved temperature-corrected thermography measurement[1] produced by the installed thermography cameras in the peak zone on PERC solar cells
- Mapping through analysing script



[1]D. Ourinson et al., AIP Conference Proceedings, 2019

Fraunhofer ISE

Inline Wafer Temperature Measurements

Measurement Results with the IR Camera System

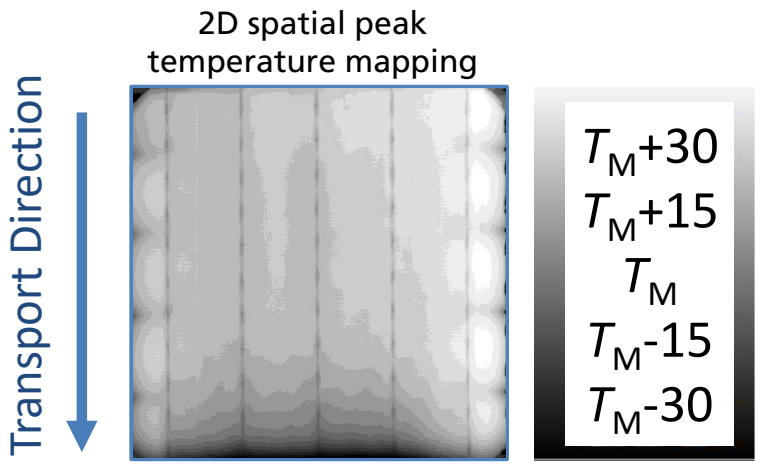
- Spatially resolved temperature-corrected thermography measurement[1] produced by the installed thermography cameras in the peak zone on PERC solar cells
- Mapping through analysing script

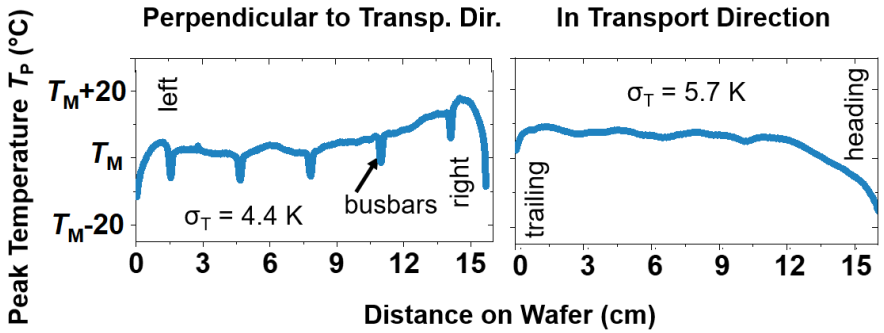
In transport direction

- Homogeneous temperature for most parts
- Slightly cooler heading part of the wafer

Perpendicular to transport direction

- Optical effects at the busbars





[1]D. Ourinson et al., AIP Conference Proceedings, 2019

Fraunhofer ISE

Inline Wafer Temperature Measurements

Measurement Results with the IR Camera System

- Spatially resolved temperature-corrected thermography measurement[1] produced by the installed thermography cameras in the peak zone on PERC solar cells
- Mapping through analysing script

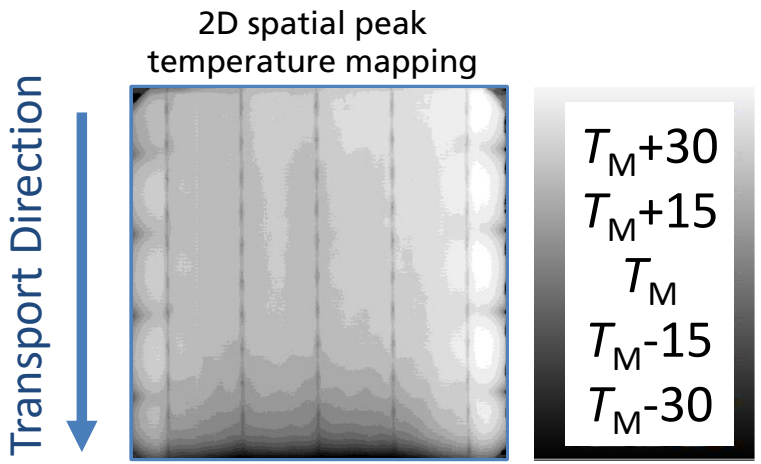
In transport direction

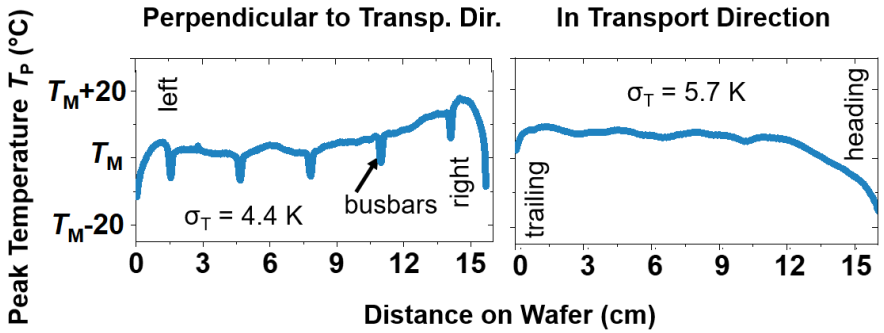
- Homogeneous temperature for most parts
- Slightly cooler heading part of the wafer

Perpendicular to transport direction

- Optical effects at the busbars

→ Complete wafer temperature distribution during peak phase





[1]D. Ourinson et al., AIP Conference Proceedings, 2019

Fraunhofer ISE

COO Investigation
“High-speed” Firing Processes and IR Camera System Integration

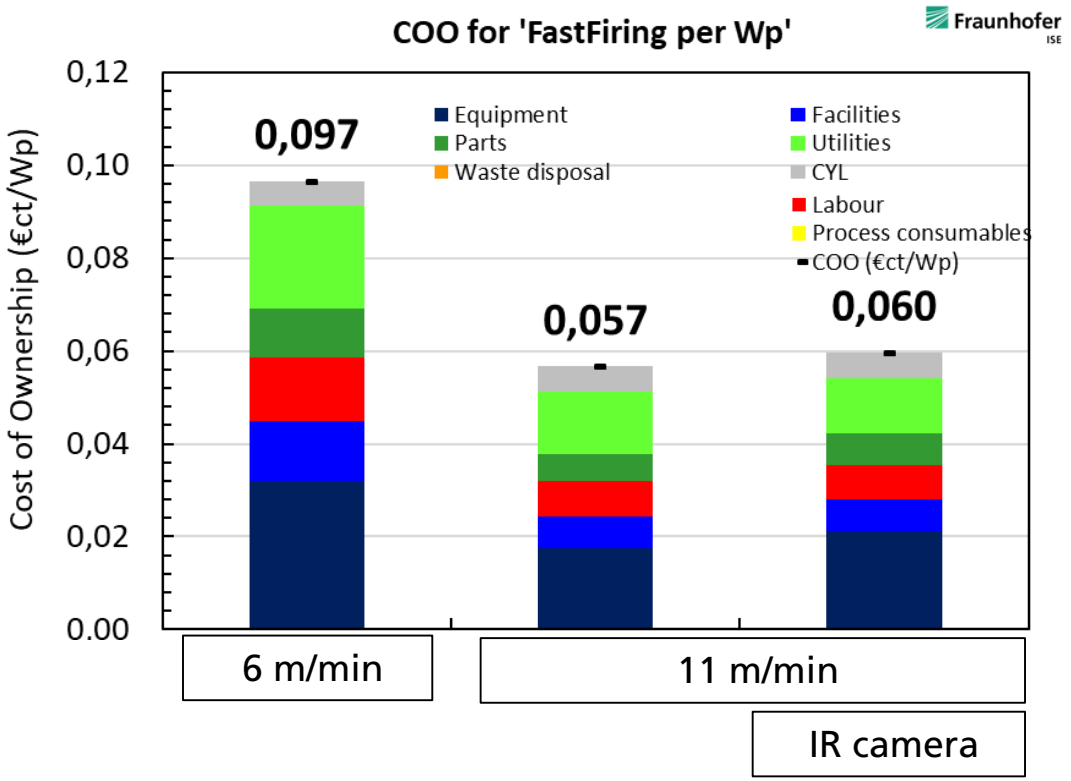
- Cost of Ownership for the integration of a high-end IR camera system into an industrial firing furnace (cost/W_{peak})
- Assumptions:
  - Industrial dual lane fast firing furnace
  - High belt velocity of 11 m/min

[1] S. Nold, Dissertation 2019

COO Investigation
“High-speed” Firing Processes and IR Camera System Integration

- Cost of Ownership for the integration of a high-end IR camera system into an industrial firing furnace (cost/W_{peak})
- Assumptions:
  - Industrial dual lane fast firing furnace
  - High belt velocity of 11 m/min
  - Sharpening of the efficiency distribution and thus an increase of the average cell efficiency of the production of 0,1%$_{abs}$

→ Inline wafer measurement is no cost driver for a production line



[1]COO results of the FF-processes with integration of a high-end IR camera

[1] S. Nold, Dissertation 2019

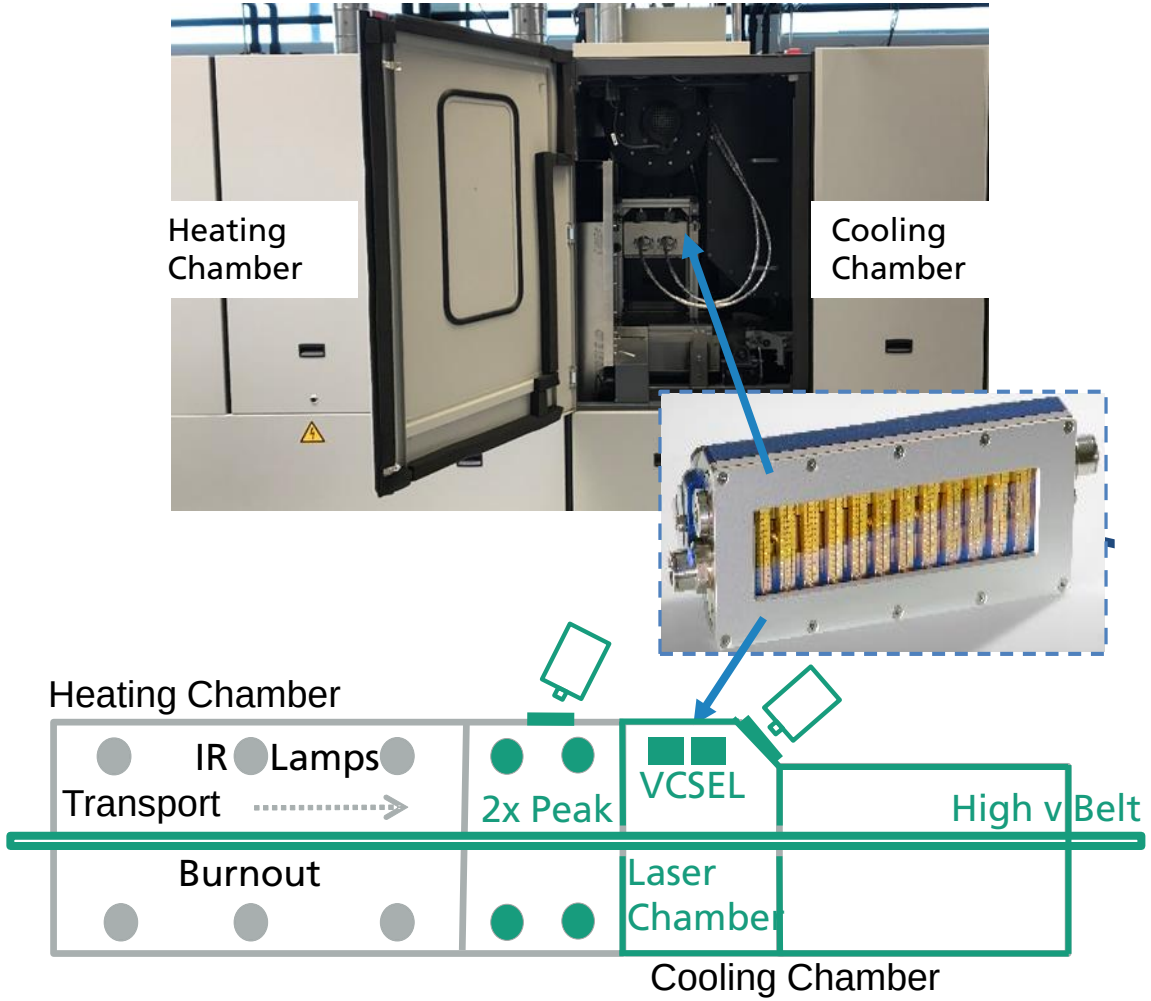
Fraunhofer ISE

Alternative Firing Technology[1]

Laser Firing Process – Setup and Profiles

1. Higher throughput for industrial production
2. Integration of IR camera for process control
3. Evaluation of alternative Laser Firing Technology

- Integration of two ~5 kW VCSEL-Modules after the classic peak zone and before the cooling zone
- Optimizing homogeneity mainly through:
  - Spatial power profiles
  - Mirrors as „side walls“ parallel to the transport direction



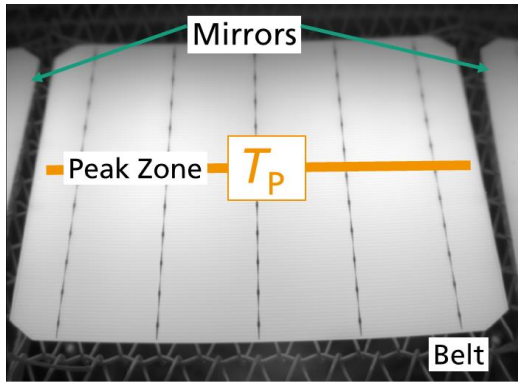
[1]D. Ourinson et al., JPV, 2020, tbp

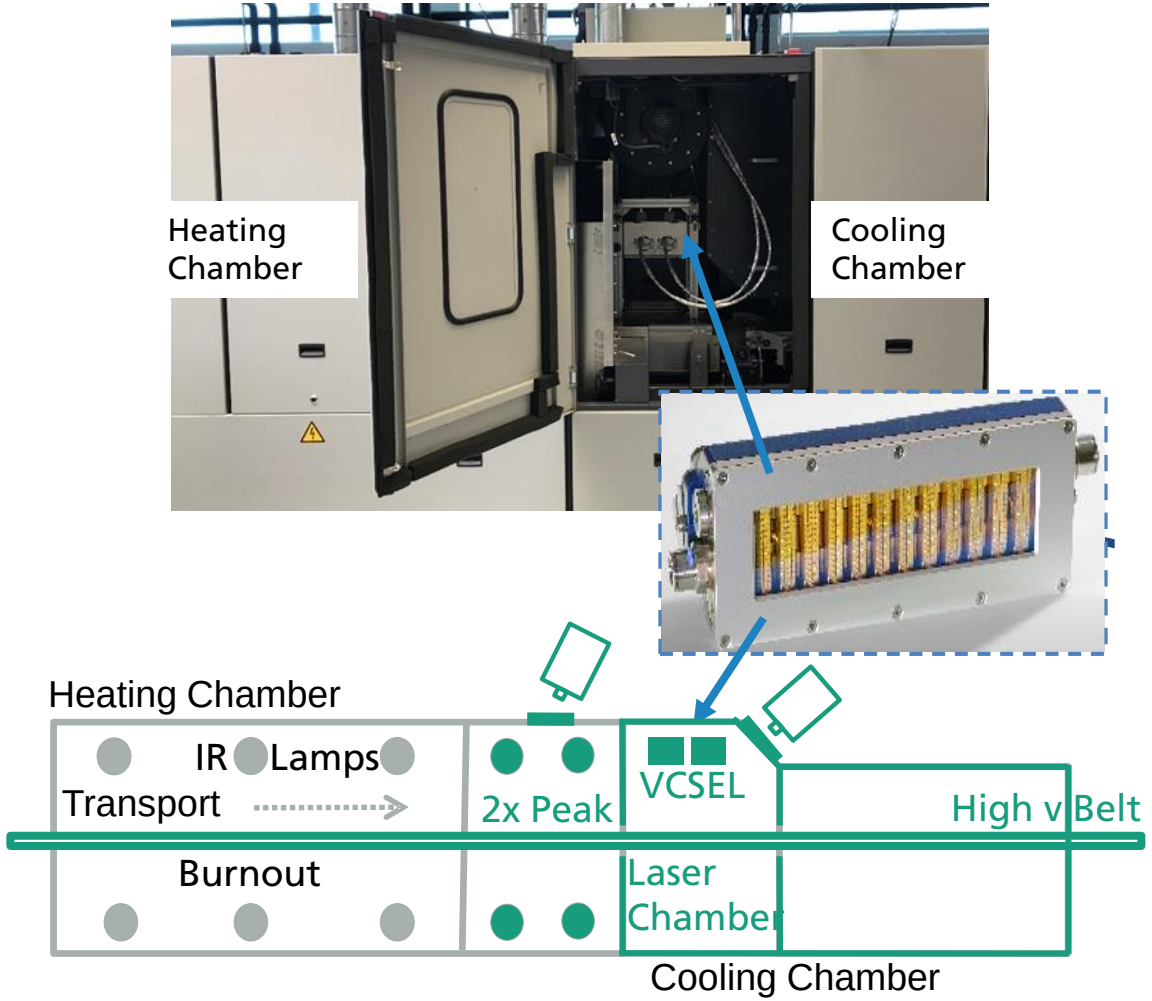
Alternative Firing Technology[1]

Laser Firing Process – Setup and Profiles

1. Higher throughput for industrial production
2. Integration of IR camera for process control
3. Evaluation of alternative Laser Firing Technology

- Integration of two ~5 kW VCSEL-Modules after the classic peak zone and before the cooling zone
- Optimizing homogeneity mainly through:
  - Spatial power profiles
  - Mirrors as „side walls“ parallel to the transport direction
- IR camera essential to optimise process





[1]D. Ourinson et al., JPV, 2020, tbp

Fraunhofer ISE

Alternative Firing Technology
Laser Firing Process – PERC Results

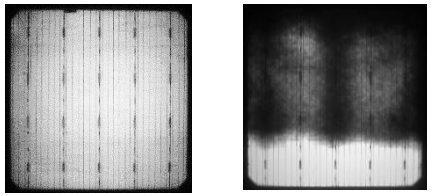
Initial: Standard H-grid

- Trailing part of the cell underfired
- Most likely appearance of "short-circuit effect"[1]

Electroluminescence (EL) images

Classic Firing	Laser Firing

Transport



pFF-FF: 1,9% 28,9%

[1]Kim *et al.*, *PiP* 2016

Fraunhofer ISE

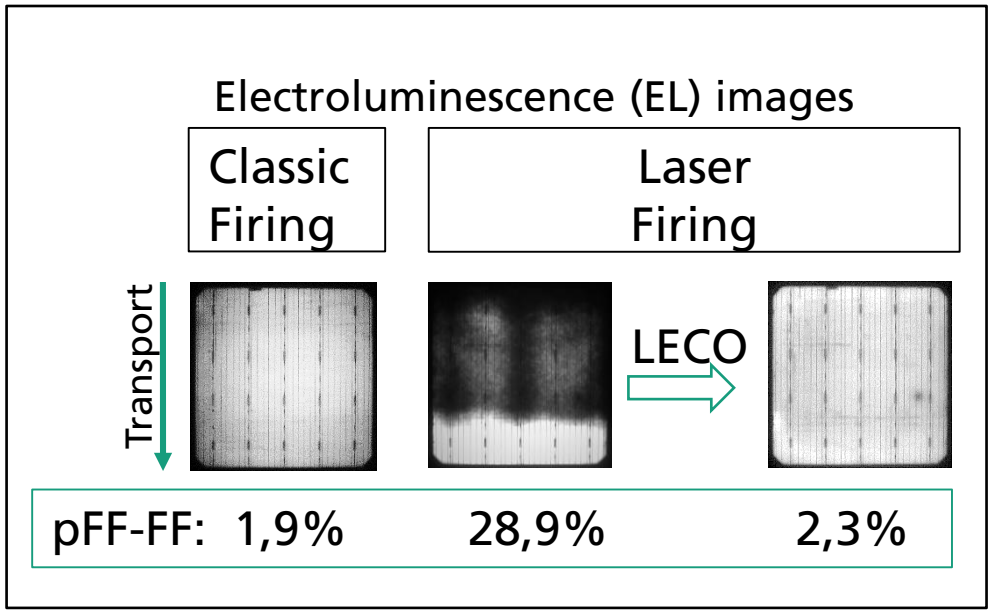
Alternative Firing Technology
Laser Firing Process – PERC Results

Initial: Standard H-grid

- Trailing part of the cell underfired
- Most likely appearance of "short-circuit effect"[1]

Optimization and solution

- Using Laser Enhanced Laser Optimization (LECO[2]) process to heal underfired Ag contacts



[1]Kim *et al.*, *PiP* 2016

[2]E. Krassowski et al., EU PVSEC, 2020

Alternative Firing Technology
Laser Firing Process – PERC Results

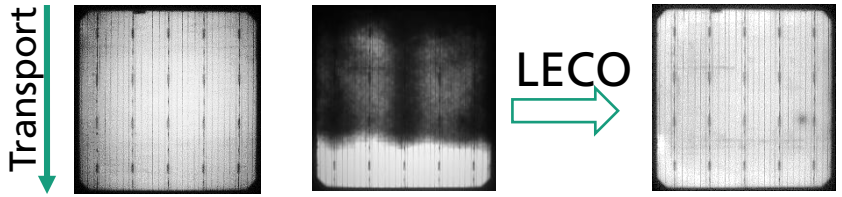
Initial: Standard H-grid

- Trailing part of the cell underfired
- Most likely appearance of "short-circuit effect"[1]

Optimization and solution

- Using Laser Enhanced Laser Optimization (LECO[2]) process to heal underfired Ag contacts
- Busbar-less Ag-grid[3]

Electroluminescence (EL) images



pFF-FF: 1,9% 28,9% 2,3%

Busbars	With		Without	
Firing	Laser	Classic	Laser	Classic
η (%)	20,3	21,9	22,0	22,1
pFF-FF (%)	5,9	2,1	2,5	1,8

I-V measurements of best Laser-firing process

[1]Kim *et al.*, *PiP* 2016
[3]Chu *et al.* *IEEE* 2018

[2]E. Krassowski et al., EU PVSEC, 2020

Alternative Firing Technology
Laser Firing Process – PERC Results

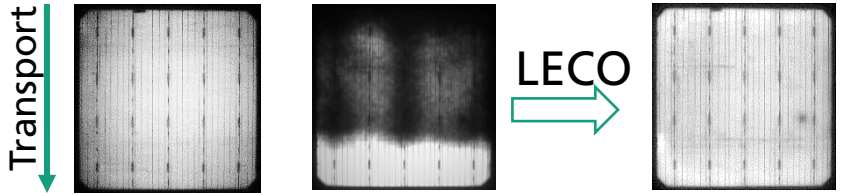
Initial: Standard H-grid

- Trailing part of the cell underfired
- Most likely appearance of "short-circuit effect"[1]

Optimization and solution

- Using Laser Enhanced Laser Optimization (LECO[2]) process to heal underfired Ag contacts[2]
- Busbar-less Ag-grid[3]
- Interrupted busbar Ag grid (standard module interconnection possible)

Electroluminescence (EL) images



pFF-FF: 1,9% 28,9% 2,3%

Busbars	With		Without		Interrupted	
Firing	Laser	Classic	Laser	Classic	Laser	Classic
η (%)	20,3	21,9	22,0	22,1	21,4	21,6
pFF-FF (%)	5,9	2,1	2,5	1,8	2,2	2,1

I-V measurements of best Laser-firing process

[1]Kim *et al.*, *PiP* 2016
[3]Chu *et al.* *IEEE* 2018

[2]E. Krassowski et al., EU PVSEC, 2020

Alternative Firing Technology
Laser Firing Process – PERC Results

Initial: Standard H-grid

- Trailing part of the cell underfired
- Most likely appearance of "short-circuit effect"[1]

Optimization and solution

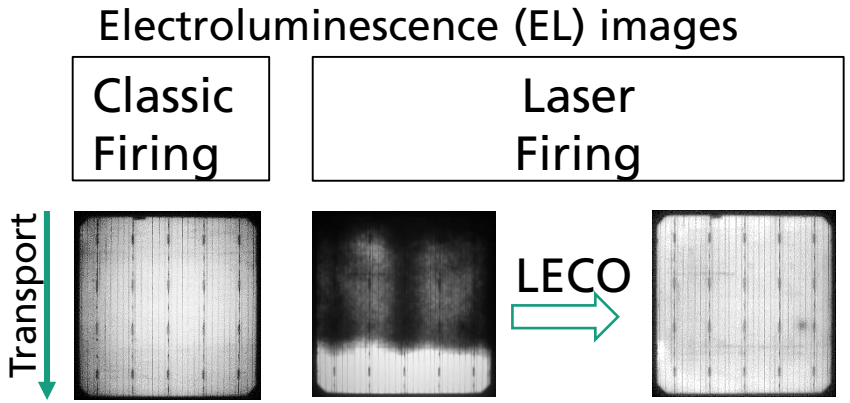
- Using Laser Enhanced Laser Optimization (LECO[2]) process to heal underfired Ag contacts[2]
- Busbar-less Ag-grid[3]
- Interrupted busbar Ag grid (standard module interconnection possible)

Best process

- Only 0,1%$_{abs}$ lower efficiency for best laser fired cells

→ Potential of laser firing could be shown

Electroluminescence (EL) images



pFF-FF: 1,9% 28,9% 2,3%

Busbars	With		Without		Interrupted	
Firing	Laser	Classic	Laser	Classic	Laser	Classic
η (%)	20,3	21,9	22,0	22,1	21,4	21,6
pFF-FF (%)	5,9	2,1	2,5	1,8	2,2	2,1

I-V measurements of best Laser-firing process

[1]Kim *et al.*, *PiP* 2016
[3]Chu *et al.* *IEEE* 2018

[2]E. Krassowski et al., EU PVSEC, 2020

Alternative Firing Technology
Technology Assessment (Laser vs. Classic)

Advantages for laser firing technology

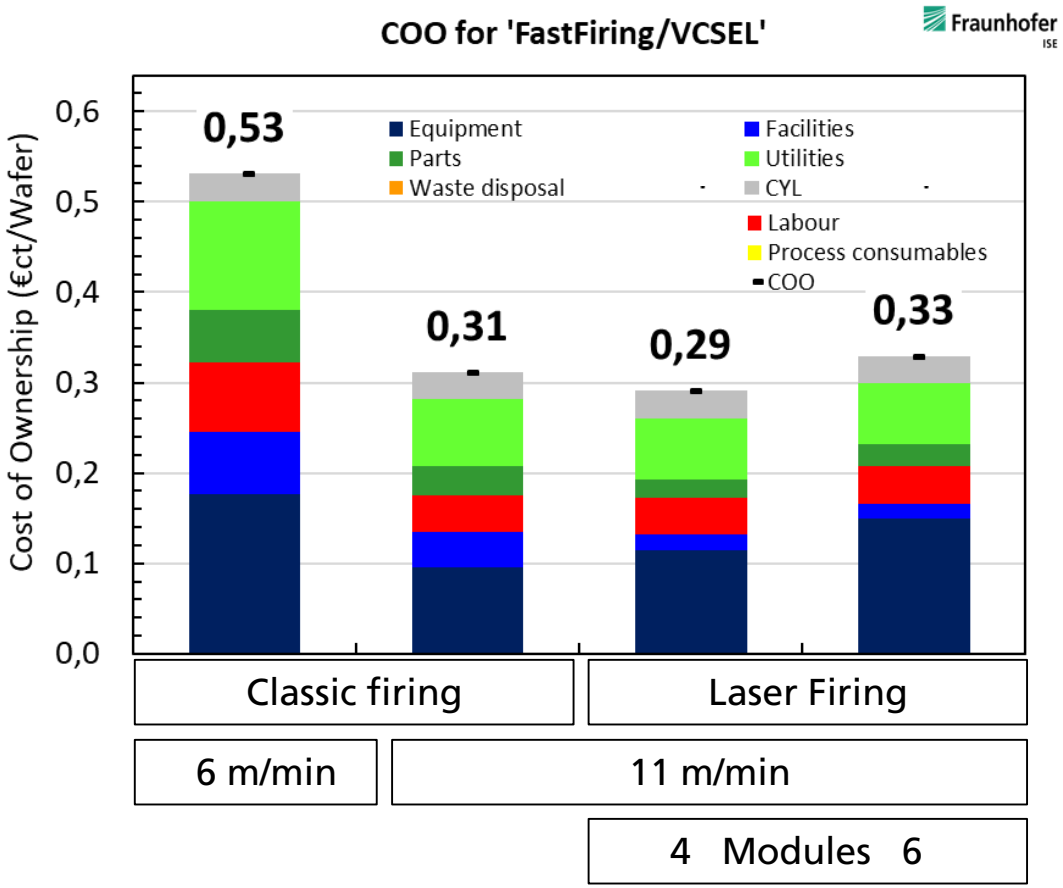
- Smaller footprint
- Lower power consumption
- Low temperature surrounding
- Direct heating by VCSEL laser
  (steeper ramps possible)

Alternative Firing Technology
Technology Assessment (Laser vs. Classic)

Advantages for laser firing technology

- Smaller footprint
- Lower power consumption
- Low temperature surrounding
- Direct heating by VCSEL laser (steeper ramps possible)
- COO investigation (€ct/Wafer) is equal to the classic firing technology

→ Potential of laser firing technology



Fraunhofer ISE

Conclusions and Outlook

Within the Feuerdrache project we could realize:

- Advanced conventional firing process (higher throughput)
- The proof of IR thermography being a inline suitable, contact-less and cost neutral measurement system
- Establishment of laser firing technology and process

Conclusions and Outlook

Within the Feuerdrache project we could realize:

- Advanced conventional firing process (higher throughput)
- The proof of IR thermography being a inline suitable, contact-less and cost neutral measurement system
- Establishment of laser firing technology and process

Conventional firing process:

- Investigation on even faster firing processes (“high-speed processes”)

Inline thermography measurement:

- Correlation of real wafer peak-temperature with solar cell I-V parameters

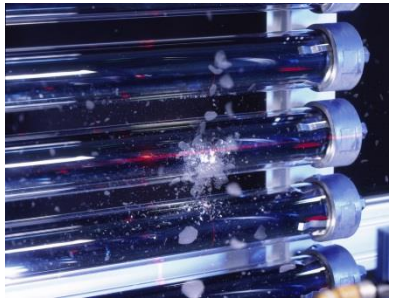
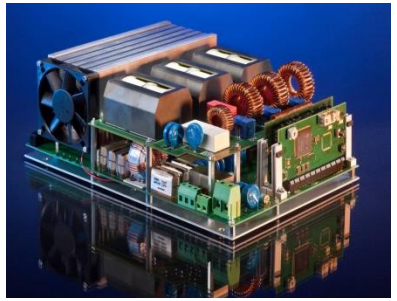
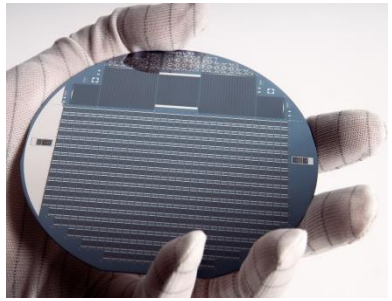
Laser firing process and technology:

- Process development on TOPCon cells
- Optimized laser firing process and equipment

Thank you for your Attention!

Thanks to all co-workers




Fraunhofer Institute for Solar Energy Systems ISE

Gernot Emanuel

www.ise.fraunhofer.de

Gernot.emanuel@ise.fraunhofer.de

This work was supported within the research project “FEUERDRACHE“ (0324205B).

Supported by:

Federal Ministry for Economic Affairs and Energy

on the basis of a decision by the German Bundestag

Fraunhofer ISE