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

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9th Metallization & Interconnection Workshop
Online Conference, 05.10.2020

www.ise.fraunhofer.de
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**

Cross-section scheme of industrial furnace
Motivation and Aims
Improving Firing Process and Evaluating Alternative Technologies

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- Project aims
  1. Higher throughput for industrial production

Cross-section scheme
(in green changes to industry)
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  2. Integration of IR camera for process control
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  3. Evaluation of alternative Laser Firing Technology

Cross-section scheme
(in green changes to industry)

¹VCSEL - vertical cavity emitting surface laser
Higher Belt Velocity Firing Profiles

Measurements taken by thermocouples on PERC solar cells

- Variation in the belt velocity up to nearly double speed
- Maintaining the peak shape and the cooling ramp
- Adaption of burnout profiles\textsuperscript{1,2}
  - From shorter plateau up to “ramp”
- Ramp for “High-speed” processes

\textsuperscript{1}D. Ourinson et al., SiPV, 2019
\textsuperscript{2}D. Ourinson et al., AIP, 2019
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
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Results

- Efficiency compared to the standard process identical
- No difference in series resistance
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
Inline Wafer Temperature Measurements
Setup and Integration of IR Camera System

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

1. D. Ourinson et al., PSS-RRL, 2019
2. D. Ourinson et al., Metallization Workshop, 2019
3. D. Ourinson et al., JoVE, 2020
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
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
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
Inline Wafer Temperature Measurements
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- Spatially resolved temperature-corrected thermography measurement\(^1\) produced by the installed thermography cameras in the peak zone on PERC solar cells
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  - 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
**Inline Wafer Temperature Measurements**

**Measurement Results with the IR Camera System**

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**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

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1D. Ourinson et al., AIP Conference Proceedings, 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

1 S. Nold, Dissertation 2019
COO Investigation
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- 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

\[ \text{COO for 'FastFiring per Wp'} \]

\[ \begin{align*}
\text{6 m/min} & : 0.097 \\
\text{11 m/min} & : 0.057, 0.060
\end{align*} \]

\[ ^1 \text{COO results of the FF-processes with integration of a high-end IR camera} \]

1 S. Nold, Dissertation 2019
Alternative Firing Technology\(^1\)
Laser Firing Process – Setup and Profiles

- Integration of two \(\sim 5\) 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. Higher throughput for industrial production
2. Integration of IR camera for process control
3. Evaluation of alternative Laser Firing Technology

\(^1\)D. Ourinson et al., JPV, 2020, tbp
Alternative Firing Technology¹
Laser Firing Process – Setup and Profiles

- 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

¹D. Ourinson et al., JPV, 2020, tbp
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"\(^1\)

\(^1\)Kim et al., PiP 2016
Alternative Firing Technology
Laser Firing Process – PERC Results

Initial: Standard H-grid
- Trailing part of the cell underfired
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Optimization and solution
- Using Laser Enhanced Laser Optimization (LECO²) process to heal underfired Ag contacts

¹Kim et al., PiP 2016
²E. Krassowski et al., EU PVSEC, 2020
**Alternative Firing Technology**

**Laser Firing Process – PERC Results**

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

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**Electroluminescence (EL) images**

<table>
<thead>
<tr>
<th>Classic Firing</th>
<th>Laser Firing</th>
</tr>
</thead>
<tbody>
<tr>
<td>pFF-FF: 1,9%</td>
<td>28,9%</td>
</tr>
<tr>
<td>2,3%</td>
<td></td>
</tr>
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**I-V measurements of best Laser-firing process**

<table>
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<tr>
<th>Busbars</th>
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1Kim et al., PiP 2016
2E. Krassowski et al., EU PVSEC, 2020
3Chu et al. IEEE 2018
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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)

\[ \begin{array}{c|c|c|c|c|c|c|c} \hline
\text{Busbars} & \text{With} & \text{Without} & \text{Interrupted} \\
\hline
\text{Firing} & \text{Laser} & \text{Classic} & \text{Laser} & \text{Classic} & \text{Laser} & \text{Classic} \\
\hline
\eta (\%) & 20,3 & 21,9 & 22,0 & 22,1 & 21,4 & 21,6 \\
pFF-FF (\%) & 5,9 & 2,1 & 2,5 & 1,8 & 2,2 & 2,1 \\
\hline
\end{array} \]

I-V measurements of best Laser-firing process

\(^1\)Kim et al., PiP 2016
\(^2\)E. Krassowski et al., EU PVSEC, 2020
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Best process
- Only 0,1\(^\text{abs}\) lower efficiency for best laser fired cells

→ Potential of laser firing could be shown

### Electroluminescence (EL) images

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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)
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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

![COO for 'FastFiring/VCSEL' chart](chart.png)

- **Classic firing**
  - 6 m/min
  - Cost of Ownership (€ct/Wafer): 0.53

- **Laser Firing**
  - 11 m/min
  - Cost of Ownership (€ct/Wafer): 0.31

4 Modules  6
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

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

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