FLEXO-PRINTED BUSBARLESS SOLAR CELLS FOR MULTI-WIRE INTERCONNECTION

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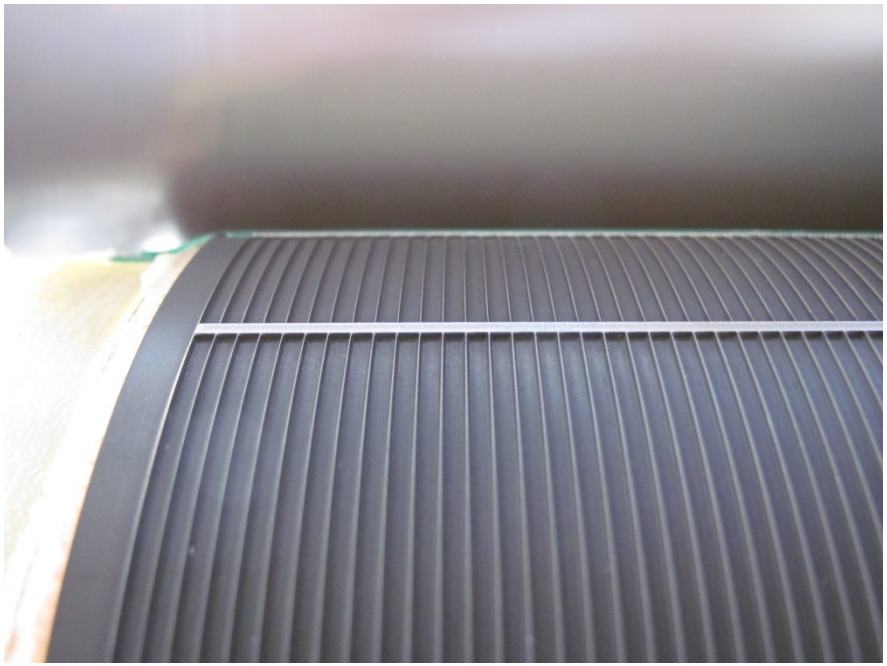
Outline

1. Motivation
2. Approach – Flexographic printing technology
3. Experimental Setup
4. Results of flexo printed busbarless solar cells and mini-module
5. Summary & Outlook

Motivation

Alternative Technologies for Solar Cell Metallization

- Aim:
  Rotational printing methods for solar cell metallization
- Advantages:
  - High throughput (factor 2-3 compared to screen printing)
  - Very low silver consumption
  - Low costs for consumables
  - Highly developed printing process with commercially available consumables



Fine line front side metallization of silicon solar cells using Flexographic printing

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Joint Project
„Rock-Star“

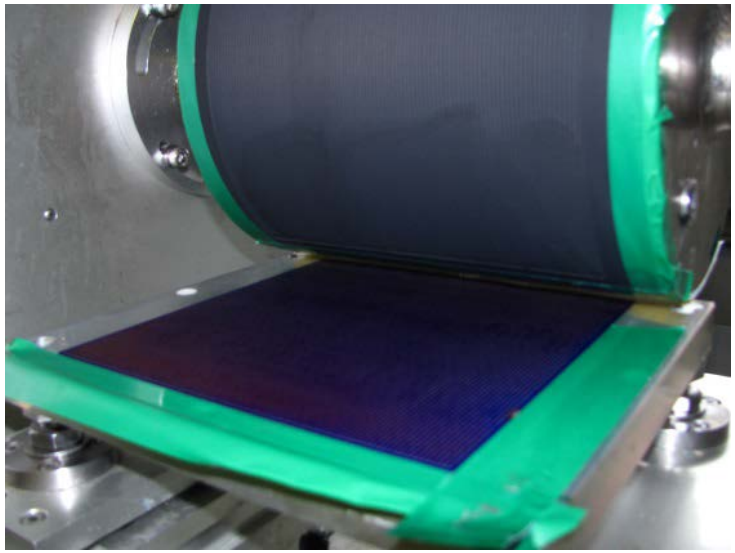
- Joint project „Rock-Star“
- 11 industry partners
- Time scale: 01.09.2015 – 31.08.2018
- Supported by the German Federal Ministry of Education and Research (BMBF) (Photonics Research Germany)
- Aim of project:
  - Evaluation of rotational printing methods
  - Development of a platform with rotational printing units

Project Consortium:

Associated partners:

Approach
Flexographic Printing Technology

- Flexography – letterpress printing principle
- Widely used in graphic arts industry
- High-speed roll-to-roll machines
- Introduced in 2011 by ISE and TU Darmstadt [1]
- Feasibility on Solar Cells confirmed in several studies [2-4]



Flexo printing platform for solar cell metallization

[1] M. Frey et al., Energy Procedia 11 (2011)
[2] A. Lorenz et al., 29th EUPVSEC (2013)
[3] A. Lorenz et al., J. Print Media Techn. Res. 4, 2014
[4] S. Thibert et al., Prog. Photovoltaics (2015)

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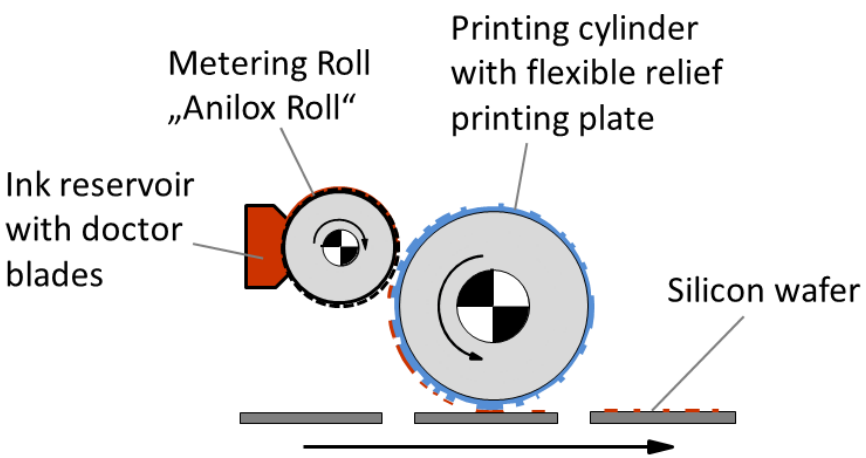
Approach
Flexographic Printing Technology

- Wafer fixed on vacuum table
- Low-viscous ink
- Direct printing on wafer
- Printing speed V_p = 300 mm/s on lab machine
- Expected throughput on an industrial machine:
  3000 – 5000 Wafers/h

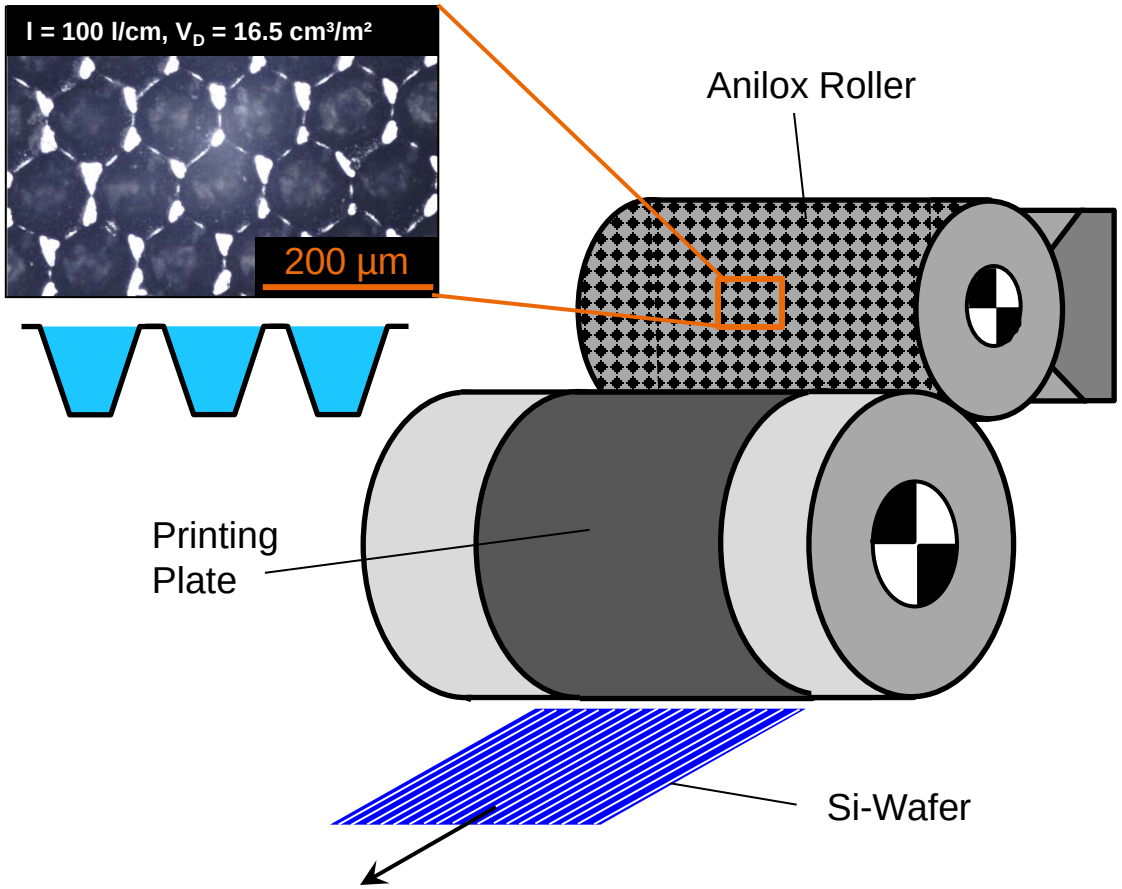


Schematic view of a flexographic printing unit for solar cell metallization

Approach
Flexographic Printing Technology

Anilox Roller:

- Line screening
  100 – 700 wells/cm
- Dip Volume D_v
  1.0 – 17.0 cm³/m²
- Large wells:
  More ink transferred
- Small wells:
  Less ink transferred



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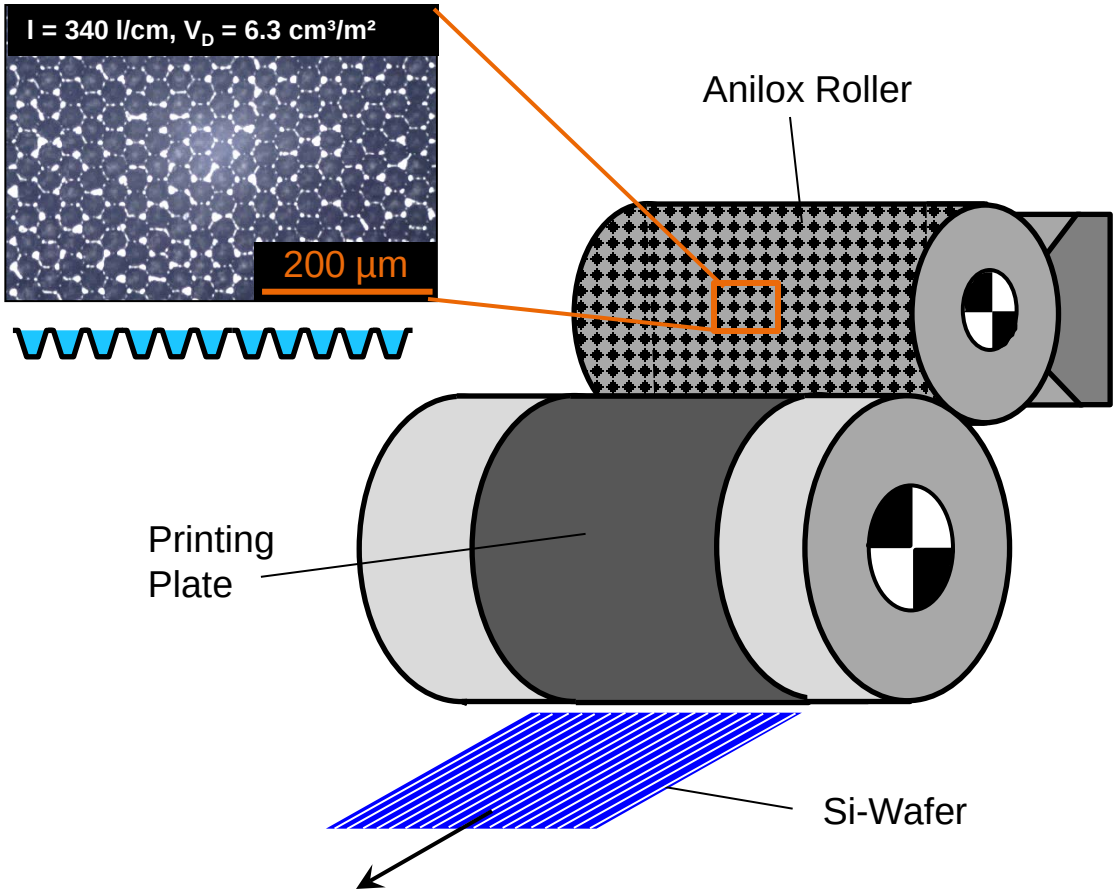

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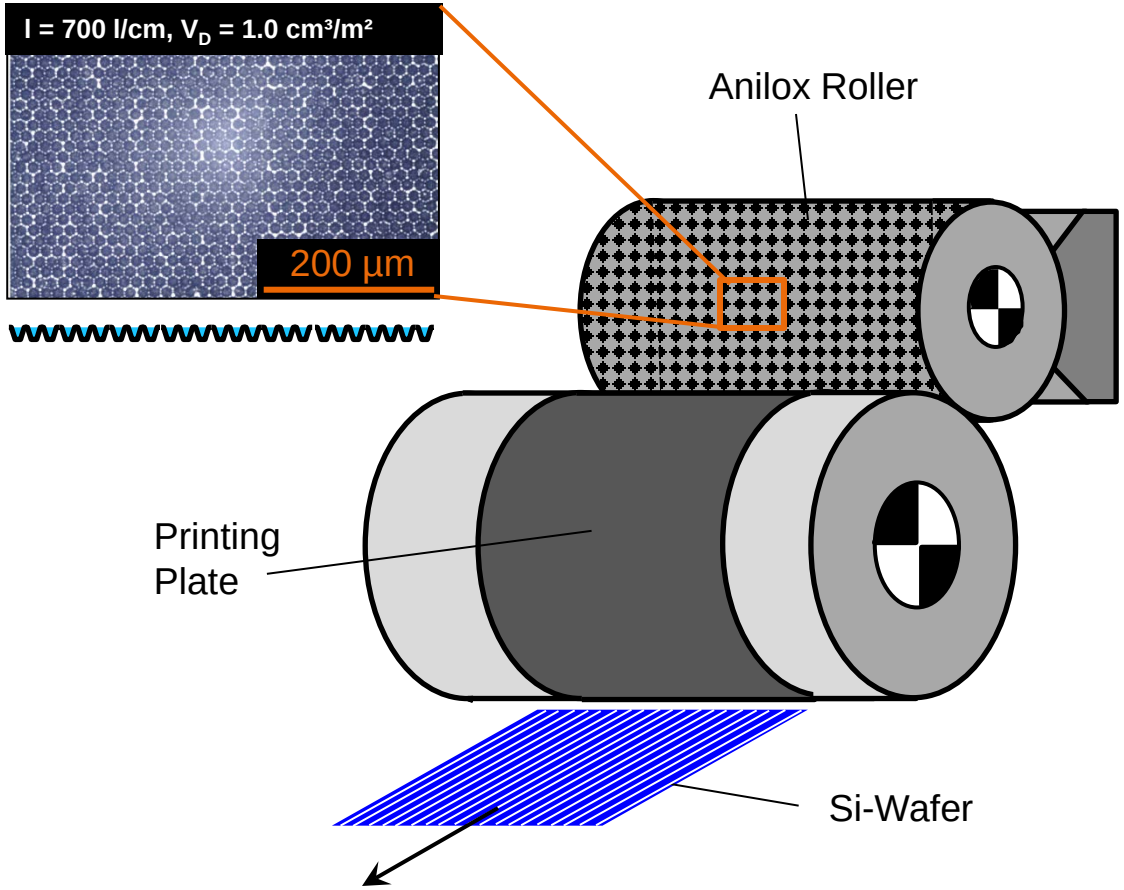
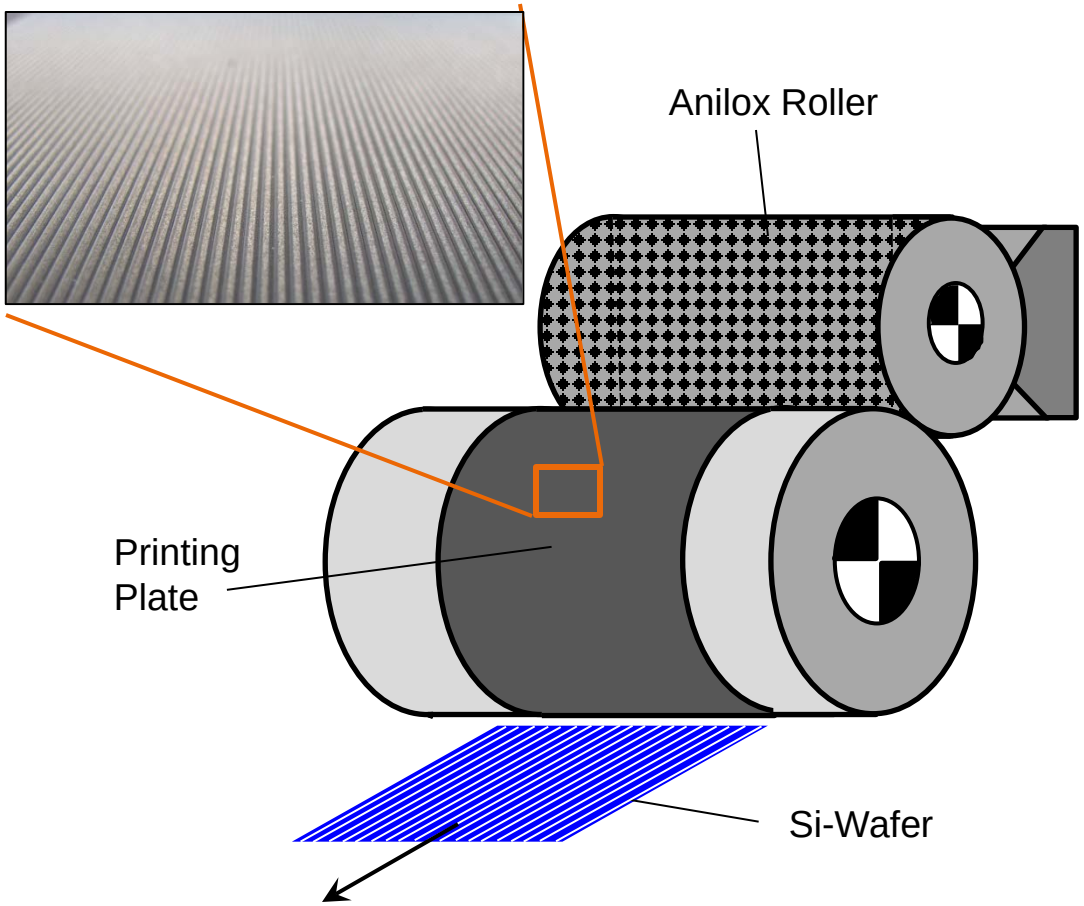


Approach
Flexographic Printing Technology

Printing plate:

- Flexible plate
- Printing areas elevated
- UV exposed or laser-engraved plates
- Mounted on cylinder with compressible foam tape
- Width of finger ridge down to w_n = 5 µm



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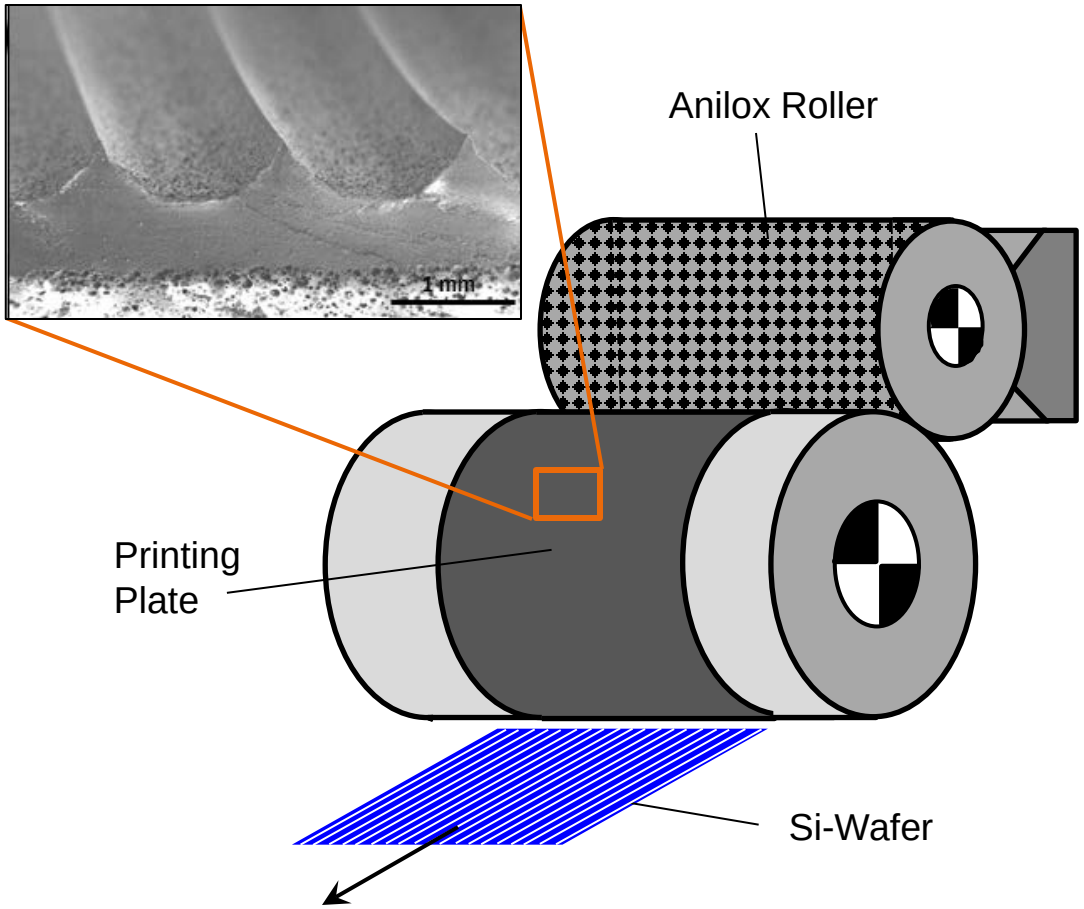
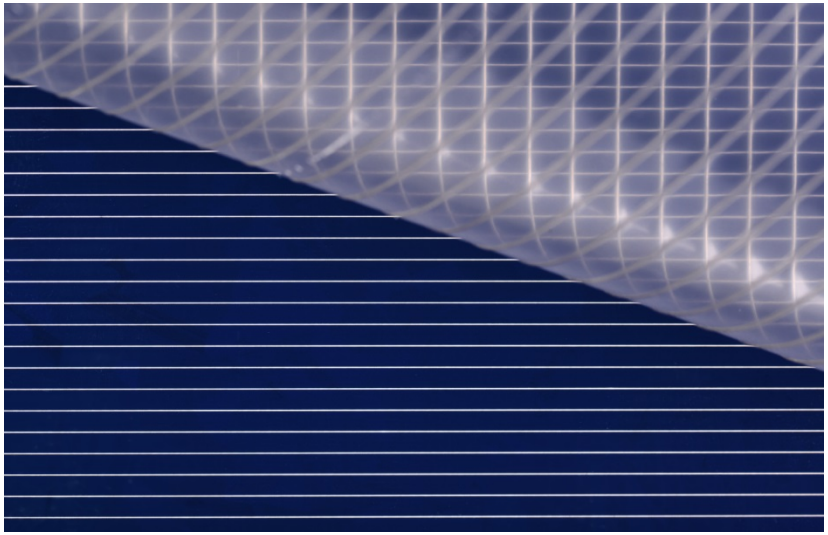


Approach
Smart Wire Connection Technology

Smart Wire Connection Technology (SWCT) [5]:

- Interconnection of busbarless solar cells by 15 to 38 Wires
- Wires embedded in polymer foil (foil-wire-electrode)
- Advantages:
  - Reduced ohmic power losses
  - Low silver consumption
  - Less shading losses
  - Less impact of cell breakage



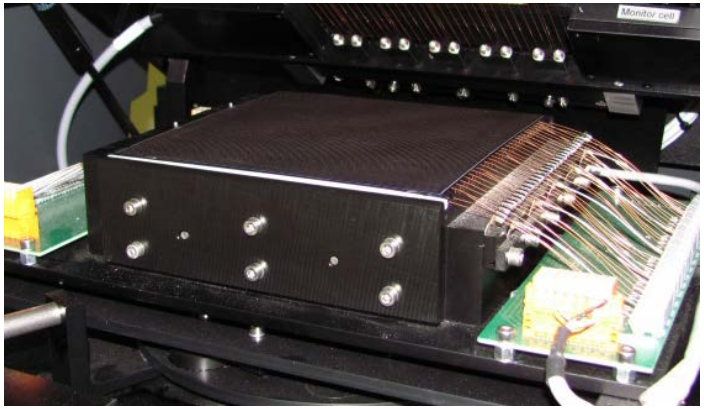
Multi-wire interconnection with Meyer Burger's Smart Wire Connection Technology
(Source: Meyer Burger AG)

[5] T. Söderström et al., 28th EUPVSEC, 2013

Experimental Setup
Fabrication of busbarless solar cells

Experimental setup:

- Pre-test to investigate impact of printing pressure
- Fabrication of busbarless solar cells with flexo-printed front side



I-V-measurement using Pasan Grid^{TOUCH}-system

Cz-Si Precursor ($R_{sh} \approx$ 85-90 Ω/sq)

Screen printed Al rear side

Flexo printing on front side

Ink A | Ink B

Firing variation

I-V-measurement (Pasan Grid^{TOUCH})

Confocal laser microscopy (fingers)

Measurement of finger resistance R_L

TLM-measurement (contact resistance ρ_c)

Fabrication of mini-module (SWCT)

I-V-measurement module

EL-measurement of module

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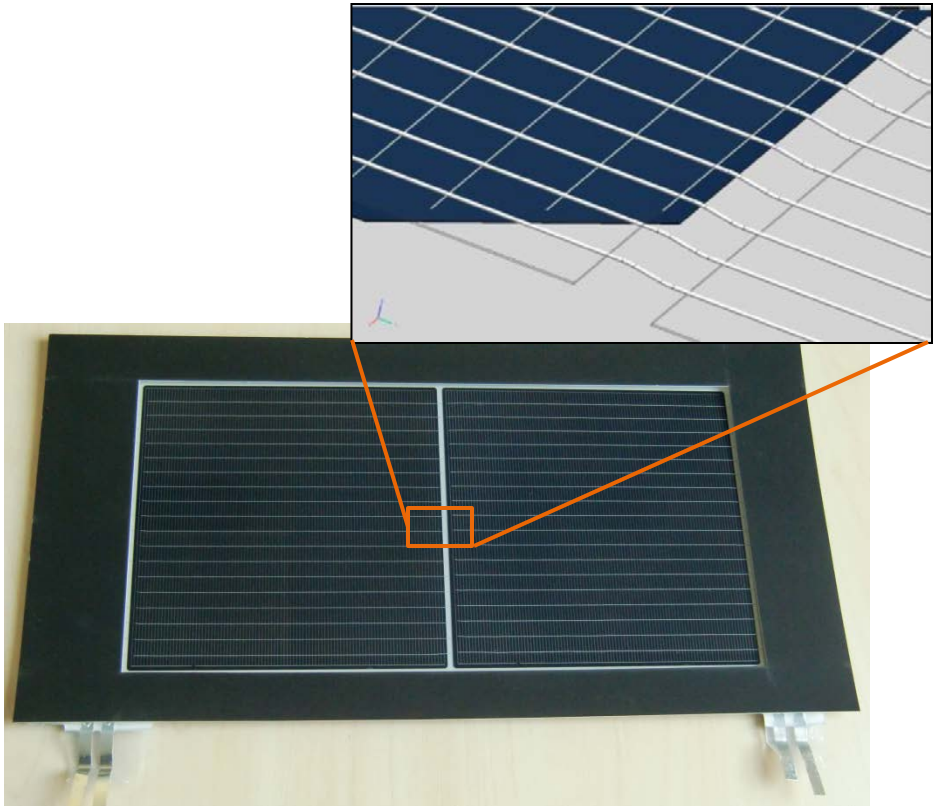
Experimental Setup
Fabrication of Mini-Module

Experimental setup:

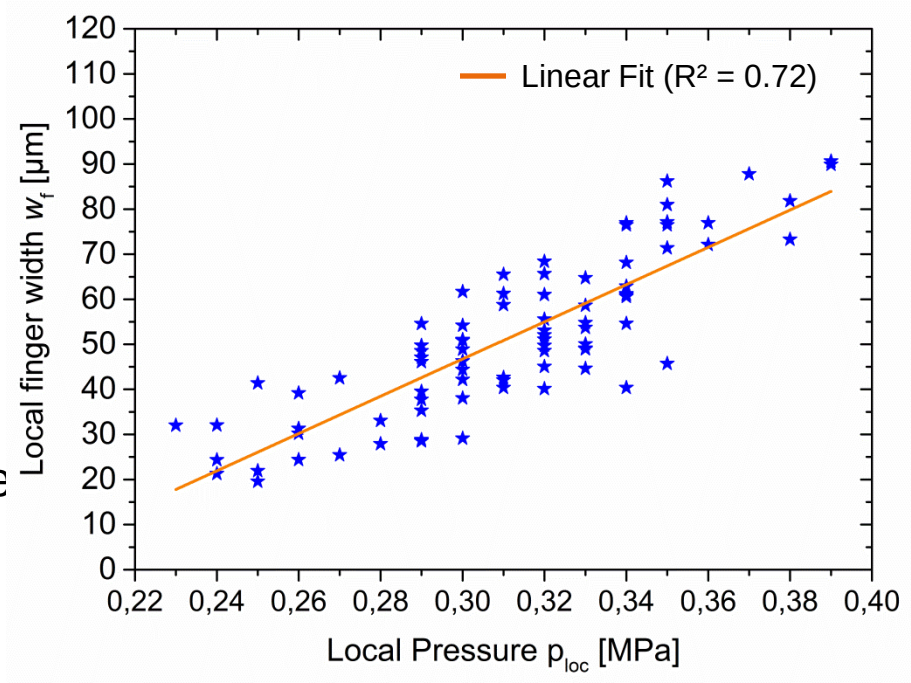
- Fabrication of mini module with the best 2 solar cells
- SWCT wire interconnection with 18 wires
- Encapsulated with TPO and glass



Fabricated mini-module of two flexo-printed busbarless solar cells with SWCT interconnection
(Source: MeyerBurger/Fraunhofer ISE)

Experimental Results
Impact of printing pressure

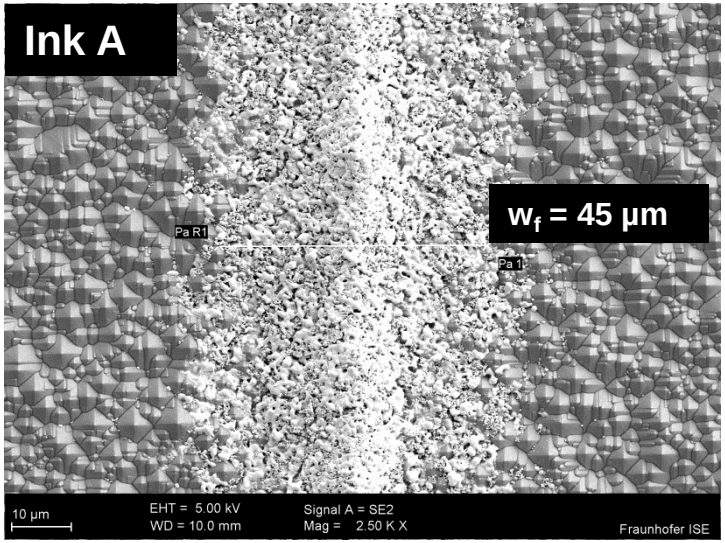
- Pre-test to investigate the impact of printing pressure p_{loc} on finger width w_f
- *Fujifilm Prescale* sensor films
- Linear relationship:
  Δp_{loc} = 0.05 Mpa → $\Delta w_f \approx$ 10 µm
- Printing pressure strongly affects the finger width
- absolute precise adjustment is required



Correlation between local pressure p_{loc} and finger width w_f

Experimental Results
Results of Ag-inks

- Aim of further research:
  Control and reduce ink spreading
  → less shading
  → increase conductivity of fingers
- Ink A showed a considerable lower contact resistance



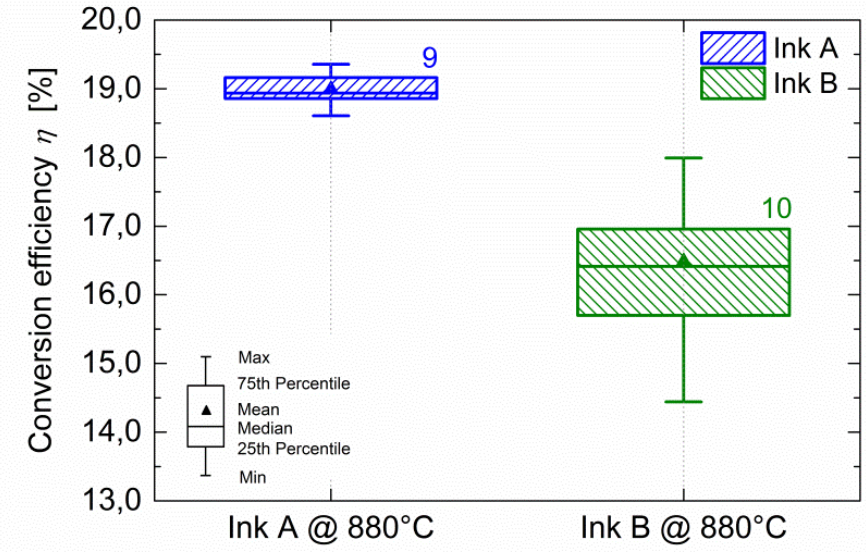
SEM image of flexo-printed contact finger

Ink	Viscosity η [mPas]	∅ Finger width w_f [µm]	∅ Finger Resistance R_L [Ω/cm]	∅ Spec. Contact resistance ρ_c [mΩcm²]
A	358*	55 (σ = 7)	19.5 ± 4.0**	3.0 ± 0.6**
B	113*	66 (σ = 6)	18.3 ± 1.9**	19.0 ± 5.2**

*measured at a shear rate of $1000 s^{-1}$ **95% confidence interval

Experimental Results
I-V-results of busbarless solar cells

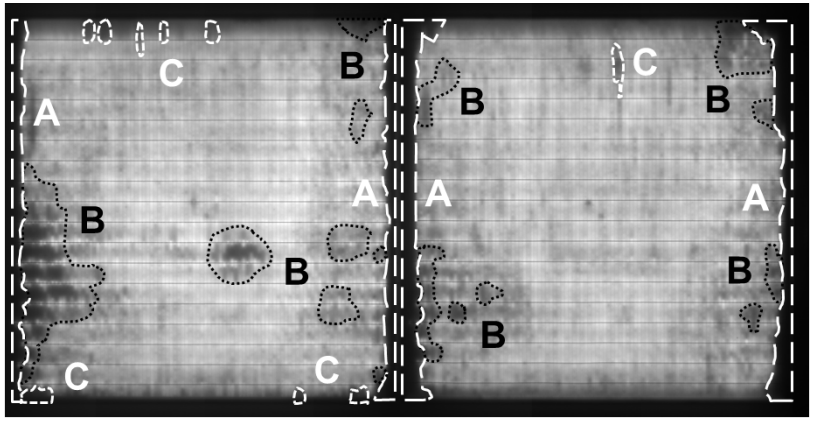
- Only **4.7 mg wet ink** applied on front side
- Best group (ink A @ T_{FFO} = 880°C): $\eta_{\varnothing}$ = 19.0 % (best cell η_{max} = 19.4 %)
- Ink B achieved considerably lower results due to the high ρ_c $\eta_{\varnothing}$ = 16.5 %
- Measurement characteristics of Grid^{TOUCH}:
  - j_{sc} without shading of wires
  - *FF* measured with 30 wires



Conversion efficiency η of the best solar cell groups with both inks

Experimental Results
I-V-results of SWCT mini-module

- Successful interconnection via SWCT
- Aperture module efficency (black mask): $\eta_{\varnothing}$ = 15.8 %
- Causes for cell-to-module losses:
  - *FF* losses due to finger R_L (30-38 wires optimal)
  - Additional shading of wires
  - EL revealed further causes for *FF*-losses



EL image with identified defects:
A) defective wire-interconnection to contact fingers along the edges of the solar cells
B) Areas with high R_s on solar cells
C) Locally failed interconnections between contact fingers and wires

Flexographic Printing for Multi-Busbar Solar Cells
Summary + Outlook

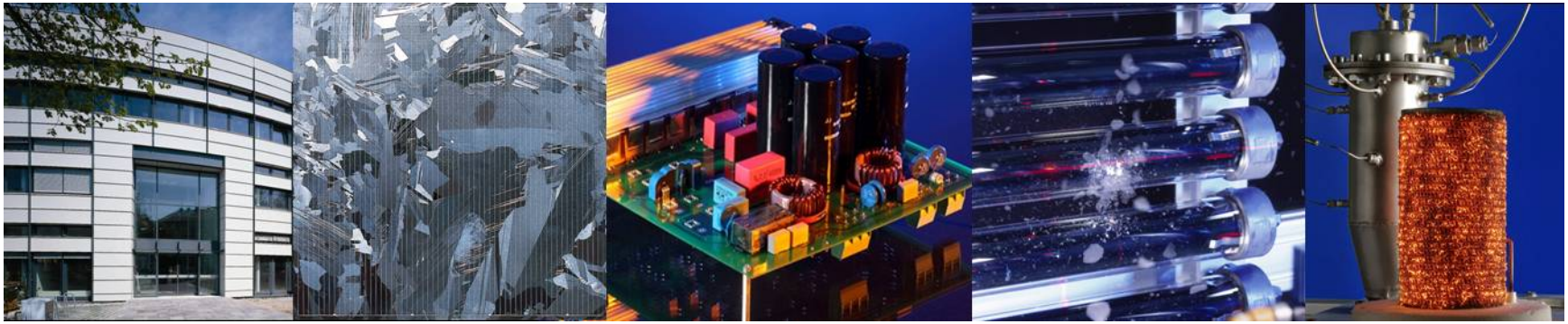
Experimental results:

- First busbarless solar cells with flexo-printed front side metallization demonstrated
- Very low ink consumption of 4.7 mg per cell
- Solar cells obtained promising results (η_{max} = 19.4 %)
- Successful fabrication of mini-module with SWCT interconnection

Challenges and further research:

- Only one printing step on the front side
- Reduce lateral finger resistance (Target: R_L < 10 Ω/cm)
- Optimize amount of wires for SWCT
- Rotary screen printing for the rear side

Thank you for your attention!



… and all Co-workers at PVTEC
… as well as our industry partners who supported this work

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