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*
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]

**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
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

$\text{Anilox Roller}$

$\text{Printing Plate}$

$\text{Si-Wafer}$

$I = 100 \text{ l/cm}, V_D = 16.5 \text{ cm}^3/\text{m}^2$

$\text{200 \( \mu \text{m} \)}$
Approach
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$I = 700$ l/cm, $V_D = 1.0$ cm³/m²

200 µm
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 $w_n = 5 \, \mu m$
Approach

Flexographic Printing Technology

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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)

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

| Cz-Si Precursor ($R_{sh} \approx 85-90 \ \Omega$/sq) |
| Screen printed Al rear side |
| Flexo printing on front side |
| Ink A | Ink B |
| Firing variation |
| I-V-measurement (Pasan GridTOUCH) |
| Confocal laser microscopy (fingers) |
| Measurement of finger resistance $R_L$ |
| TLM-measurement (contact resistance $\rho_c$) |
| Fabrication of mini-module (SWCT) |
| I-V-measurement module |
| EL-measurement of module |

*I-V-measurement using Pasan GridTOUCH-system*
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 $p_{\text{loc}}$ on finger width $w_f$
- *Fujifilm Prescale* sensor films
- Linear relationship: $\Delta p_{\text{loc}} = 0.05 \text{ Mpa} \rightarrow \Delta w_f \approx 10 \text{ µm}$
- Printing pressure strongly affects the finger width
- Absolute precise adjustment is required

*Correlation between local pressure $p_{\text{loc}}$ 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

<table>
<thead>
<tr>
<th>Ink</th>
<th>Viscosity $\eta$ [mPas]</th>
<th>$\phi$ Finger width $w_f$ [µm]</th>
<th>$\phi$ Finger Resistance $R_L$ [Ω/cm]</th>
<th>$\phi$ Spec. Contact resistance $\rho_c$ [mΩcm$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>358*</td>
<td>55 ($\sigma = 7$)</td>
<td>$19.5 \pm 4.0^{**}$</td>
<td>$3.0 \pm 0.6^{**}$</td>
</tr>
<tr>
<td>B</td>
<td>113*</td>
<td>66 ($\sigma = 6$)</td>
<td>$18.3 \pm 1.9^{**}$</td>
<td>$19.0 \pm 5.2^{**}$</td>
</tr>
</tbody>
</table>

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

SEM image of flexo-printed contact finger

SEM image of flexo-printed contact finger
Experimental Results

I-V-results of busbarless solar cells

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

Conversion efficiency $\eta$ of the best solar cell groups with both inks
Experimental Results
I-V-results of SWCT mini-module

- Successful interconnection via SWCT
- Aperture module efficiency (black mask): $\eta_{\phi} = 15.8\%$
- 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 ($\eta_{\text{max}} = 19.4 \%$)
- 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: $R_L < 10 \ \Omega/cm$)
- 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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