HIGH SPEED DISPENSING WITH NOVEL 6” PRINT HEAD

… The next step towards Industrialization …

M. Pospischil\textsuperscript{a}, M. Klawitter\textsuperscript{a},
M. Kuchler\textsuperscript{a}, M. Jahn\textsuperscript{a}, R. Efinger\textsuperscript{a},
R. Schwarz\textsuperscript{a}, L. Wende\textsuperscript{b}, M. König\textsuperscript{c},
F. Clement\textsuperscript{a} and D. Biro\textsuperscript{a}

\textsuperscript{a} Fraunhofer ISE, Freiburg, Germany
\textsuperscript{b} ASYS Automatisierungssysteme GmbH, Dornstadt, Germany
\textsuperscript{c} Heraeus Deutschland GmbH & Co. KG, Hanau, Germany

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Design of Industrial PV Metallization Lines
Dispenser as Drop-In-Replacement

With busbarless cell interconnection

Single SP

- Screen Printed (SP) Rear Side
- Ag-Solderpads + Aluminum

Double SP

- SP-Front: Finger Grid
- Drying
- SP-Front: Busbars + Grid

Dual SP

- SP-Front: Finger Grid
- Drying
- SP-Front: Busbars

Alternative (Dual) Print

- SP-Front: Busbars
- Dispenser: Finger Grid

Dispenser: Drop-In-Replacement

Drying + Contact Sintering

Characteristics of Dispensed Contact Fingers
Improved Effective Silver Utilization and Contact Optics

- Significantly improved finger homogeneity increases effective silver utilization by ~15%
- High Aspect Ratio (AR) decreases relative effective width (EW) by 25% compared to screen printing
Influences of Rheology
How to reach higher Aspect Ratios

\[ Ca = \frac{\tau_y \cdot D}{2\sigma} = \frac{\text{viscous stresses}}{\text{surface tension}} \]

- \( \tau_y \) (kPa): yield stress
- \( D \) (\( \mu m \)): nozzle diameter
- \( \Gamma \left( \frac{mN}{m} \right) \): surface tension

- \( AR_{el} \) linear dependent on capillary number \( Ca \)
- Minimum on Cz: \( AR_{el}^{Ca=0} \rightarrow 0.2 \)

\[ \rightarrow \text{Decrease of } D \text{ requires adaptation of rheology} \]

Aspect Ratio depending on Capillary number.
Solar Cell Results on Cz Al-BSF
Cell Efficiency Improvements using Dispensing

- > 110 dispensed cells
- Lab yield ~97%

→ Efficiency increase by dispensing: \( \Delta \eta \sim +0.3\% \text{abs.} \)

→ Reduction of wet Ag-laydown
  \( m_{\text{Ag,D40-R}} \sim 70-80\text{mg (without BB)} \)

![Graph showing cell conversion efficiency with Ag wet: 120mg, 125mg, 100mg for S(1x), S(2x), D40-R respectively.](image)

References
Dispensing Technology

Application: Front Side Metallization of Silicon Solar Cells

- Non-impact, single step metallization using industrial (Ag-) printing pastes
- Application of ultrafine, homogeneous contact fingers @ \( w_f \sim 30 - 40 \ \mu m \)
- High aspect ratios (height : width) \( AR \sim 0.3-0.8 \)

→ Reduction of shading and resistive losses

- Efficiency gain compared to conventional screen printed contact (SP): \( +2\%_{\text{rel.}}, +0.4\%_{\text{abs.}} \)
- Reduced Ag-Paste consumption:
  \( m_{\text{Ag, wet}} \sim 70 - 80\text{mg} \) (-20% vs. SP)

→ Reduction of Manufacturing costs: ~1 \( \text{€ct/Wp} \)
How can we achieve 24/7 production at 1400 - 2000 wafers/h?
Parallel Dispensing Technologies
Conventional Dispensing

- Dispensing approach patented for solar cell metallization in 1992\(^{(1)}\)
- Solar cell metallization by dispensing at former Schott Solar AG, Alzenau, Germany
- Further attempts with parallel aligned n-scrrypt smart pumps \(^{(2,3)}\)

\(^{1}\) J. I. Hanoka, US005151377A (1992)
\(^{2}\) K. H. Church \textit{et al.} US2010/0055299A1
\(^{3}\) X. B. Chen \textit{et al.}, 37\textsuperscript{th} IEEE-PVSC 2011

Source: schott.com, 2007

Former solar cell production at Schott Solar AG
Parallel Dispensing Technologies
Co-Extrusion

- Co-Extrusion of paste with *reduced sol. cont.* (~74% wt. Ag) and additional *sacrificial* medium
- Enables nozzle diameters ~200µm
- Dual lane production tool with two print heads at 2700 wafer/h
- Already >100,000 cells printed, 97% uptime, >99% optical yield
- Line width of 23µm achieved
- Intermittent operation (fsq & psq)
- Requires active dispense gap control → limited process speed
- Print head design → grid design

Contact finger with precise line end positioning

1) M. Beutel *et al.*, SolMat 131, 64 (2014).
Fine Line Metallization by Dispensing / Extrusion
Dispensing vs. Co-Extrusion

Similarities:
- Non-Contacting approach
- Homogeneous, high AR
- Parallel Print head developed
- Sinter contact formation ¹)

Differences:
- Paste systems:
  - Solid cont.: ~25 ²) vs. ~60%vol.
  - Sacrificial Medium → Rheology
  - Active control of dispense gap
- Nozzle openings: ~200 vs. ~40µm

¹) Beutel, Silicon PV 2014
²) Reinhardt, AERC 2014
... and our way ...
Dispensing at Fraunhofer ISE
Development of Multi Nozzle Print Heads

Ag-Paste Rheology

![Graph showing Ag-Paste Rheology](image)

- Paste A: \( \tau_y = 613 \text{ Pa} \)
- Paste B: \( \tau_y = 1882 \text{ Pa} \)

Single Nozzle Dispenser

Optimized Finger Geometries

12 Pospischil et al., E. Proc. 43, 111 (2013).
Dispensing as Industrial Metallization Process

Status Quo

Multi Nozzle Print Head

- Nozzle Plates with ten nozzles
- Printing speed $v_y > 700$ mm/s

ASYS – Dispensing Platform

- Inline feasible dispensing platform
- High alignment precision
Dispensing as Industrial Metallization Process
Platform Design
The Novel 6“ Dispensing Print Head

Features

- Designed for 6“ wafers
- Central paste supply
- CFD-optimized paste distribution
- Nozzle Plates
  - freely adaptable to grid design (diameter, pitch)
  - Quick maintenance
- Prepared for automated cleaning

Novel 6“ print head, integrated in ASYS Dispensing platform at Fraunhofer ISE‘s PV-TEC production laboratory
The Novel 6“ Dispensing Print Head
Close-up View

- Diameter of inlet
  - $D_{in} = 2\text{mm}$
- Slot width
  - $w_s = 160\text{mm}$
- Interior paste volume
  - $V \sim 18\text{cm}^3$

- Current nozzle configurations

<table>
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<th>D</th>
<th>40µm</th>
<th>50µm</th>
<th>60µm</th>
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<tr>
<td>n</td>
<td>55</td>
<td>50</td>
<td>45</td>
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</table>
The Novel 6“ Dispensing Print Head
First Printing Tests

- Experimental verification of CFD-design
- Subsequent printing tests on Cz-wafers
- Analysis by means of Confocal laser scanning microscopy (CLSM)

Results
- Contact geometry: $w_f = 35 \pm 1 \mu m$ @ AR~0.5

→ Homogeneous distribution from 2mm inlet to 16cm outlet width

Lateral deviation of simulated massflowrate and measured finger width on 6“ wafer.
First Solar Cell Batch with novel 6“ Print Head
Experimental Design + IV Results on Cz-PERC

156 x 156 mm² Cz-Si PERC precursors

- Local opening of back side passivation layer (laser)
- Screen printed Al back surfaces
- Screen printed busbars (5 x 1.2mm)
- Dispensed contact fingers N =100, D = 50µm
- Fast Firing Furnace. $T_{peak} = 810, 830, 850 \, ^\circ C$, sunny side up

### IV – Characterization

<table>
<thead>
<tr>
<th></th>
<th>FF (%)</th>
<th>$J_{sc}$ (mA/cm²)</th>
<th>$V_{oc}$ (mV)</th>
<th>η (%)</th>
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<tbody>
<tr>
<td>Best</td>
<td>80.1</td>
<td>40.3</td>
<td>659</td>
<td>21.2</td>
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<tr>
<td>Median</td>
<td>79.3</td>
<td>40.2</td>
<td>657</td>
<td>21.0</td>
</tr>
</tbody>
</table>

→ Successful launching of 6“ print head on industrial PERC solar cells

→ Process optimization ongoing
Summary
Novel 6“ print head launched

- Novel Multi Nozzle Print Head, designed for 6“ wafers
- Nozzle Plates freely adaptable to grid design (diameter, pitch)
- Printing speed $v_y > 700$ mm/s
- Fingerwidth $\sim 35\pm 1\mu m \ @ \ AR\sim 0.5$
- Max. efficiency achieved on industrial Cz-PERC: $\eta = 21.2\%$

Novel 6“ print head, integrated in ASYS Dispensing platform at Fraunhofer ISE’s PV-TEC production laboratory
Outlook: Challenges of Intermittent Dispensing
Acting forces in free paste flow

- Outside the nozzle, shear rate vanishes
  \[ \tau_y \gg K\dot{\gamma}^n \]
- Depending on operating conditions and rheology, inertia, surface or yield forces dominate
- Critical transition point:
  - \( D_c \sim 32 - 99\mu m \)
  - \( v_c \sim 350 - 583 \text{ mm/s} \)
  - Has to be dealt with during intermittent dispensing!

\[
Re_y = \frac{\rho \cdot \bar{u}^2}{\tau_y} \quad Ca_y = \frac{\tau_y \cdot D}{2\sigma} \quad We = \frac{\rho \cdot \bar{u}^2 \cdot D}{2\sigma}
\]
Thank you for your attention!

… and all Co-authors and Co-workers within the Dispensing Project
… as well as our industry partners:

www.ise.fraunhofer.de
Maximilian.Pospischil@ise.fraunhofer.de
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\( \rightarrow \) Decrease of \( D \) requires adaptation of rheology

\( \rightarrow \) Consider influence of wafer surface

Aspect Ratio depending on Capillary number.
Rheological Characterization of Printing Pastes

Analysing flow curves

- Herschel-Bulkley
  \[ \eta = \frac{\tau_y}{\dot{\gamma}} + K\dot{\gamma}^{n-1} \]

- Influence of yield stress dominates at low shear rates
  \[ \text{Bi} = \frac{\tau_y}{K\dot{\gamma}^n} \gg 1 \]

- Rotational rheometers with limited applicability

- Capillary devices required for correct interpretation
Characterization of Capillary Flow
Capillary Viscosimeter

- Combination of three sets of diameters at constant L/D
- Linear Bagley correction of entrance pressure drop
- Subsequent wall slip correction according to Mooney
- Non-Newtonian Flow correction according to Weissenberg and Rabinowitsch
- Herschel Bulkley Fit with corrected capillary data and yield stress

Data of flow curve and wall slip to be used for CFD simulations

Apparent flow data obtained from three different diameters, corrected for entry pressure drop according to Bagley.
Characterization of Capillary Flow

Mooney Analysis - Determination of wall slip

Data Analysis

- Bagley: Isolation of entrance pressure drop
- Mooney: Determination of wall slip behaviour
- Weissenberg – Rabinowitsch: Non-Newtonian flow profile

Results

- Power law slip behaviour above critical wall shear stress $\tau_c \sim 4500 Pa$

$$U_s = \pm \beta(\tau)^{1/n_b}$$

Capillary measurements conducted in Goettfert Rheograph 20, (D=0.25, 0.5, 1.0mm, L/D=const.)