Process Development for a High-Throughput Fine Line Metallization Approach Based on Dispensing Technology

Rheology, CFD-Simulation and Print-Head Design


4th Workshop on Metallization for Crystalline Silicon Solar Cells,

07-08 May 2013, Konstanz, Germany
Motivation
Front-Side Metallization

Requirements:

- Robust contact formation
- High conductivity
- Few shading losses
- Little (Ag-) paste consumption


Source: Mette, A.
Screen Printing
... as Industrial Standard Metallization Process

- Established, reliable single step metallization approach
- Robust contact formation
- Relatively high throughput rates

- Finger homogeneity (meshmarks and paste spreading)
- Low aspect ratio (= height : width)
- Screen wear
- Mechanical load on wafer
Dispensing Technology for Front Side Metallization
Possibilities and Challenges

- Non-impact, single step process
- High resolution, high aspect ratio using similar Ag-pastes
- Improvement of cell-efficiencies
  \[ +0.3\%_{\text{abs}}^{(1)} \rightarrow \text{record: } 20.6\%^{(2)} \]

Challenges:

- Process stability
- Accuracy (precise line start/-stop)
- Throughput \(\rightarrow\) Parallelization

* Sources: (1) Specht et al., EUPVSEC 2010, (2) Lohmüller et al., IEEE Electron, 2011
Developing an Industrial Metallisation Process
Interacting Fields of Research and Engineering

- Rheology
- Paste Development (external)
- Simulation
- Contact Formation
- Hardware Design & Construction
- Technology & Material Evaluation
- Integration in PV Production Process
- Process Development
Rheological Characterisation
Shear Flow of Non-Newtonian Fluids

- Non-Newtonian fluids: $\eta \neq \text{const.}$
- Dispersions contain yield stress $\tau_y$

Velocity Profile (Laminar pipe flow)

Herschel Bulkley

\[ \tau(\dot{\gamma}) = \tau_y + k\dot{\gamma}^n \]
\[ \eta(\dot{\gamma}) = \frac{\tau_y}{\dot{\gamma}} + k\dot{\gamma}^{n-1} \]

Rheological Characterisation
Determination of Characteristic Yield Stress

- Increasing shear stress until paste starts to yield $\rightarrow$ yield stress $\tau_y$
- Strong influence on aspect ratio

$$\tau_{\theta, cone} \propto M \quad \gamma_{cone} \propto \phi$$

Source: Macosko, C.W., Rheology: principles, measurements, and applications. 1994: VCH.

Paste A
Paste B

$$\tau_{y,A} = 613 \text{ Pa} \quad \tau_{y,B} = 1882 \text{ Pa}$$
Rheological Characterisation
Capillary Viscosimeter

- Measurement at high shear rates
- Recording pressure drop depending on flow rate

\[ \tau_w = \frac{p_c}{4} \frac{D}{L} \]

\[ \dot{\gamma}_w = \frac{Q}{\pi R^3} \left[ 3 + \frac{1}{n} \right] \]

Source: Macosko, C.W., Rheology: principles, measurements, and applications. 1994: VCH.
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Computational Fluid Dynamics - Theory
Laws of Conservation

- **Mass**
  \[
  \frac{\partial \rho}{\partial t} = - (\nabla \cdot \rho \vec{v}) \quad \rho=\text{const.} \rightarrow \nabla \cdot \vec{v} = 0
  \]

- **Momentum**
  \[
  \rho \left( (\vec{v} \cdot \nabla) \vec{v} + \frac{\partial \vec{v}}{\partial t} \right) = - \nabla p + \nabla \tau_{ij} - \rho \omega^2 \vec{r} + \rho \vec{g} + \rho_q (\vec{x}) \cdot \vec{E}(\vec{x})
  \]
  \[
  = f_p - \sum_{n} f_n - \sum_{v} f_v
  \]

- **Energy – Dissipative heat due to friction**
  \[
  \frac{\partial \rho U}{\partial t} = - \nabla \cdot \rho U \vec{v} - \nabla \cdot q + T : D \quad \rho=\text{const.} \rightarrow \rho c_p \frac{DT}{Dt} = k_T \nabla^2 T + T : D
  \]

Source: Macosko, C.W., Rheology: principles, measurements, and applications. 1994: VCH.
Verification of Simulation
Comparison with Reality

Rheology + CFD-Simulation

Flow measurements in experiment

Rheologic Modelling

- Herschel-Bulkley \( \tau(\dot{\gamma}) = \tau_y + k\dot{\gamma}^n \)

Simulation

- Pressure \( \Delta p \) depending on flowrate

Experiment

- Conical Nozzle (\( \phi=80\mu m \))

→ Variation of Dispensing Pressure \( \Delta p \)

![Graph showing volumetric flow rate vs. dispensing pressure for two pastes (A and B). The graph includes data points for both dispensed and simulated flows, with a target line indicating the desired flow rate.](image-url)
Challenges of Dispensing
Comparison of Nozzle Geometries (Operating Pressure)

Metal Pastes

- **Rheology**: high viscous, Non-Newtonian, thixotropic, yield stress fluid
- Highly filled medium (agglomeration → clogging)

Process Demands

- Finest fingers (width~30µm) → Nozzle diameter: Ø~40µm
- Printing velocity (~200mm/s)
- Low operating pressure

\[
\Delta p_c \propto \frac{L}{D^4}
\]
Challenges of Dispensing
Comparison of Nozzle Geometries (Local Pressuredrop)

Metal Pastes

- **Rheology**: high viscous, Non-Newtonian, thixotropic, yield stress fluid
- Highly filled medium (agglomeration → clogging)

Process Demands

- Finest fingers (width~30µm) → Nozzle diameter: φ~40µm
- Printing velocity (~200mm/s)
- Low operating pressure
Challenges of Dispensing
Comparison of Nozzle Geometries (Velocity Profile)

Metal Pastes

- **Rheology**: high viscous, Non-Newtonian, thixotropic, yield stress fluid
- Highly filled medium (agglomeration $\rightarrow$ clogging)

Process Demands

- Finest fingers (width~30µm) $\rightarrow$ Nozzle diameter: $\varnothing$~40µm
- Printing velocity (~200mm/s)
- Low operating pressure
Challenges of Dispensing
Comparison of Nozzle Geometries (Shear strain rate)

Metal Pastes

- **Rheology**: high viscous, Non-Newtonian, thixotropic, yield stress fluid
- Highly filled medium (agglomeration → clogging)

Process Demands

- Finest fingers (width~30µm) → Nozzle diameter: Ø~40µm
- Printing velocity (~200mm/s)
- Low operating pressure
Challenges of Parallel Dispensing
Robust Print Head Design

Procedure:

- Homogeneous flow profile
  @ 10 nozzles with $\varnothing = 40\mu m$
- Variation of specific nozzles:
  $\varnothing = 40\mu m \rightarrow \varnothing = 45\mu m$

Impact on Dispensing Process:

- Deviation of mass flow rate 22%
- Resulting finger width $\pm 4.2\mu m$
  - Higher silver consumption
  - Possible line interruptions
  - High impact of fab. tolerances!
Developing an Industrial Metallisation Process
Interacting Fields of Research and Engineering

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- Process Development
Transfer into Prototype
Parallel Dispensing Print-Head

Modular Setup

- Print-head with paste distribution
- Exchangeable Nozzle-Adapter
- $10 \times \varnothing = 40\mu m$, Pitch: $1.55mm$
Developing an Industrial Metallisation Process
Interacting Fields of Research and Engineering
Evaluation

Printing Tests and First Cell Processing

Printing Results

- Low system pressure (~4 bar)
- Homogeneous flow profile @ 10 nozzles achieved

Processing of Cell Batch

- 156x156 mm² Cz p-type Si
- Standard Al + preprinted Busbars
- Efficiency increase 0.2% abs. compared to screen printing (grid not yet optimized)
- Finger widths on cells: 30±1µm

→ Record finger widths < 30µm
Parallel Dispensing Process
Summary + Outlook

Rheology + Simulation:

- Successful integration of shear rheology into CFD-simulation
- Verification of paste model and steady state simulation
- Evaluation of different nozzle and print-head designs using CFD

→ Development of a 10 nozzle parallel dispensing unit

Hardware + Process:

- Launching of novel 10-nozzle print-head prototype successful
- First cell processing demonstrated, \( \eta \approx +0.2\% \text{abs.} \)
- Line width < 30\(\mu\)m demonstrated

→ Outlook: Advanced cell processing + start & stop accuracy
Thank you for your attention!

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

This work was supported by the German Federal Ministry of Environment, Nature Conservation and Nuclear Safety under contract number 0325404.

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