HIGH SPEED DISPENSING WITH NOVEL 6’’ PRINT HEAD

… The next step towards Industrialization …

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b) ASYS Automatisierungssysteme GmbH, Dornstadt, Germany
c) Heraeus Deutschland GmbH & Co. KG, Hanau, Germany

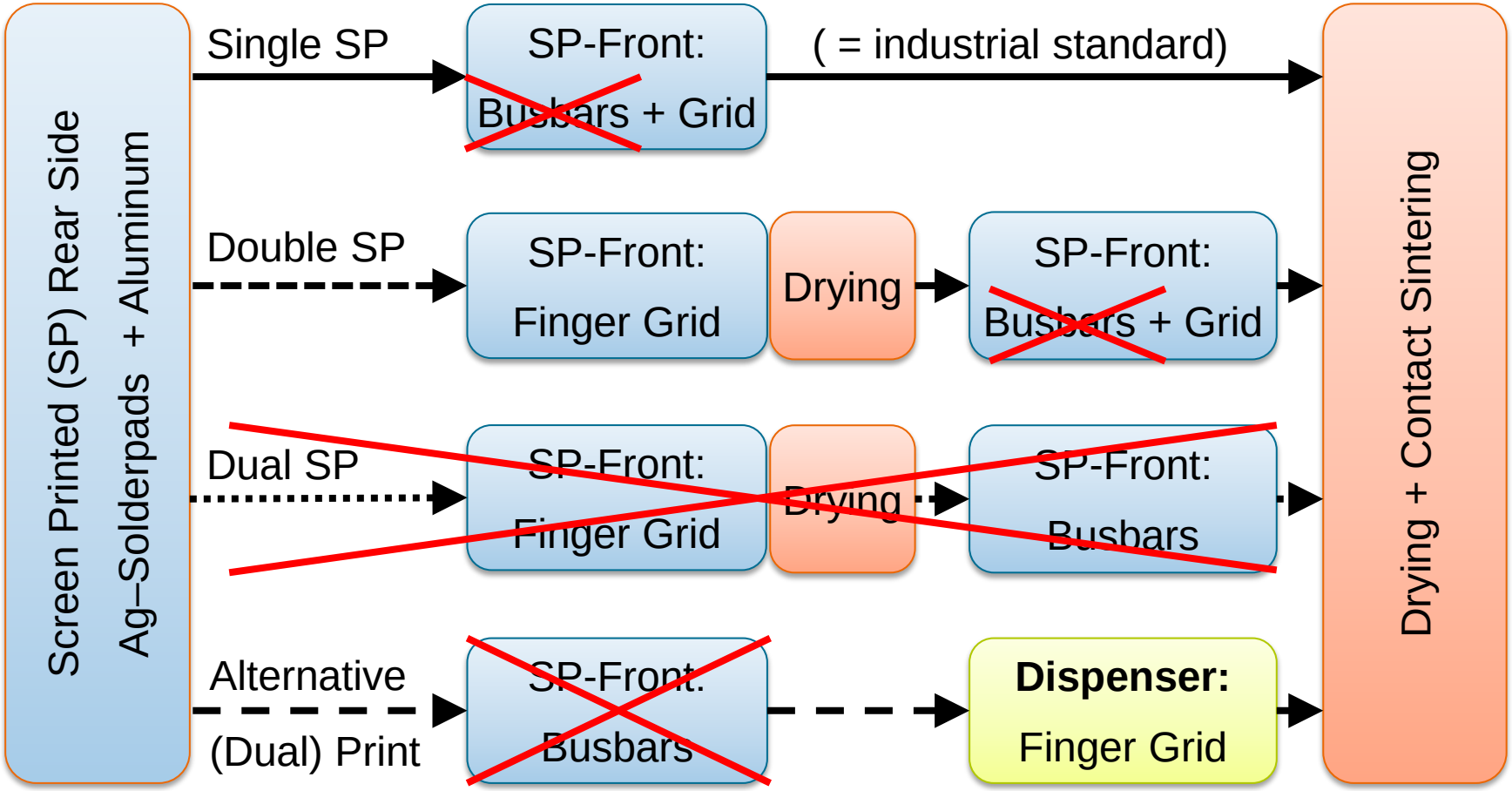
6th Workshop on Metallization and Interconnection

Constance, Mon, May 2nd, 2016

Fraunhofer ISE

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

With busbarless cell interconnection



Pospischil, M., et al., Energy Procedia **67**, 138 (2015).

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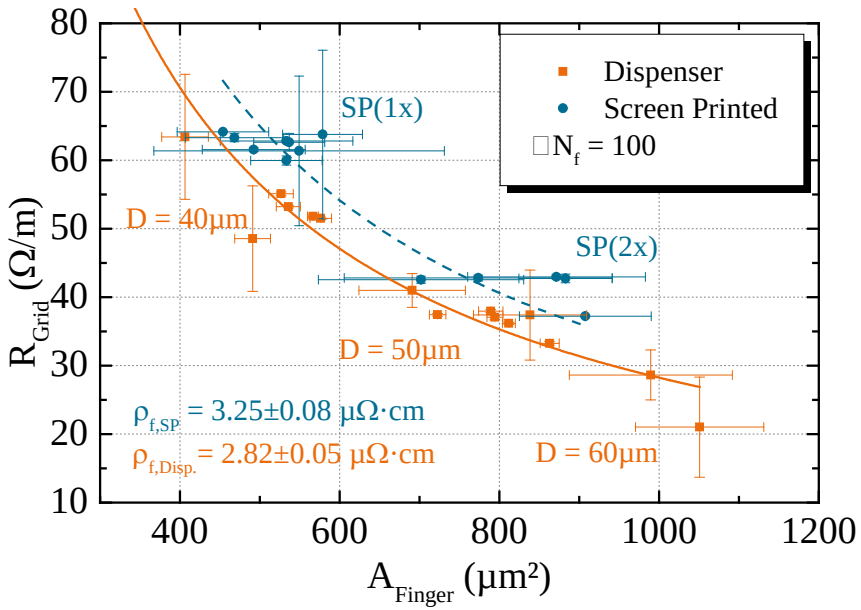
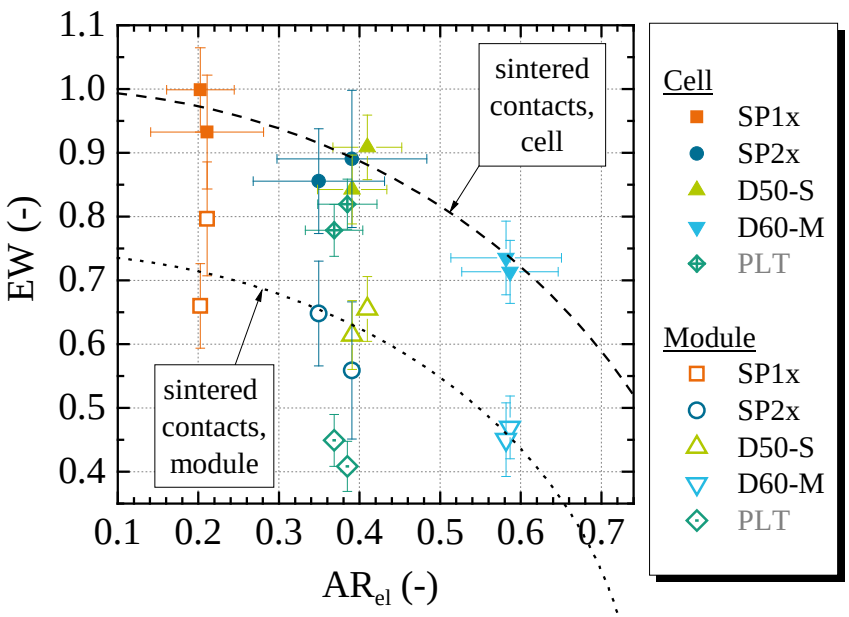
Characteristics of Dispensed Contact Fingers

Improved Effective Silver Utilizationand 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

Pospischil, M., et al., Energy Procedia **67**, 138 (2015).
Rodriguez et al., 31st EUPVSEC, Hamburg (2015)
Pospischil, M. Thesis, Uni. Freiburg, submitted 2016

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Influences of Rheology

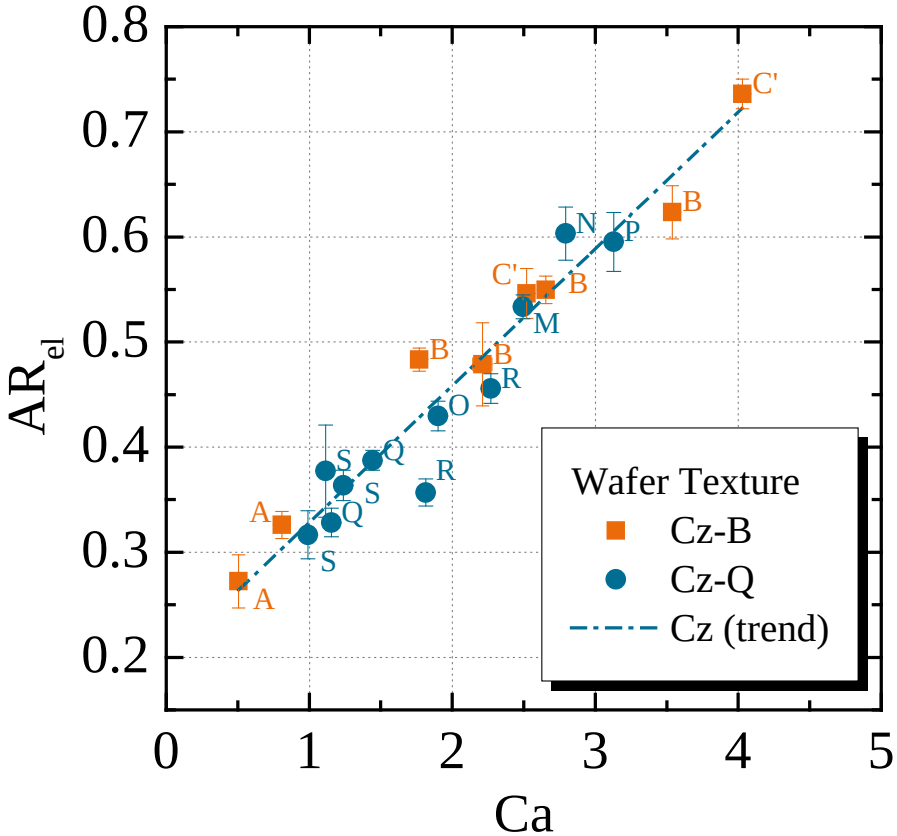
How to reach higher Aspect Ratios

$$Ca = \frac{\tau_y \cdot D}{2\sigma} = \frac{viscous\ stresses}{surface\ tension}$$

- τ_y (kPa): yield stress
- D (μm): nozzle diameter
- Γ $\left(\frac{mN}{m}\right)$: surface tension

- **AR_{el}** linear dependent on capillary number **Ca**
- Minimum on Cz: $AR_{el} \xrightarrow{Ca=0} 0.2$

→ **Decrease of D requires adaptation of rheology**



Aspect Ratio depending on Capillary number.

Pospischil, M. Thesis, Uni. Freiburg, submitted 2016

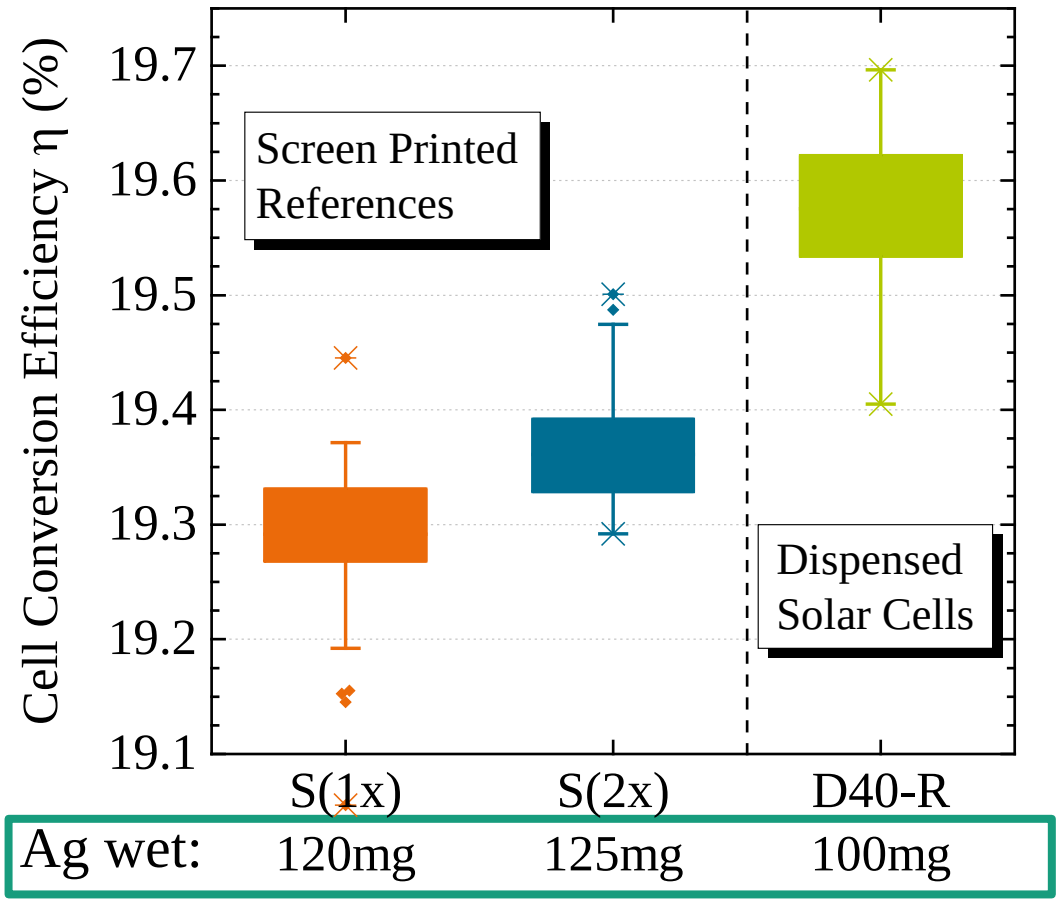
Solar Cell Results on Cz Al-BSF

Cell Efficiency Improvements using Dispensing

- > 110 dispensed cells
- Lab yield ~97%

→ Efficiency increase by dispensing:
$\Delta\eta$ ~ +0.3%abs.

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



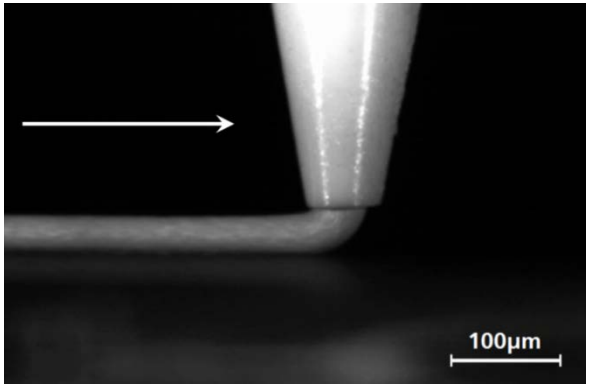
Pospischil, M., et al., 31st EUPVSEC, Hamburg, Germany (2015)

Dispensing Technology

Application: Front Side Metallization of Silicon Solar Cells

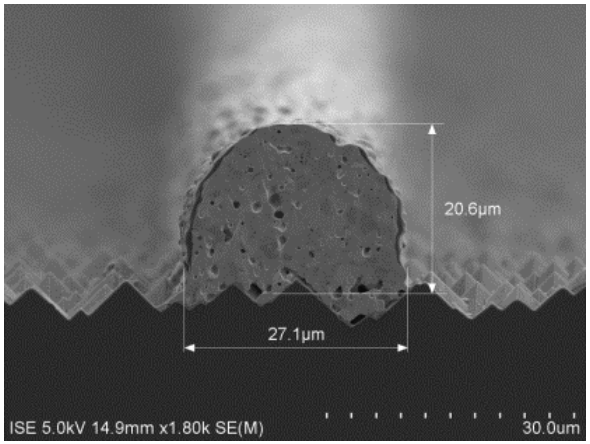
- Non-impact, single step metallization using industrial (Ag-) printing pastes
- Application of ultrafine, homogeneous contact fingers @ w_f ~ 30 - 40 µm
- high aspect ratios (height : width) AR ~ 0.3-0.8

→ **Reduction of shading and resistive losses**



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

→ Reduction of Manufacturing costs: ~**1 €ct/W$_p$**



 Pospischil, M., et al., 31st EUPVSEC, Hamburg, Germany (2015)

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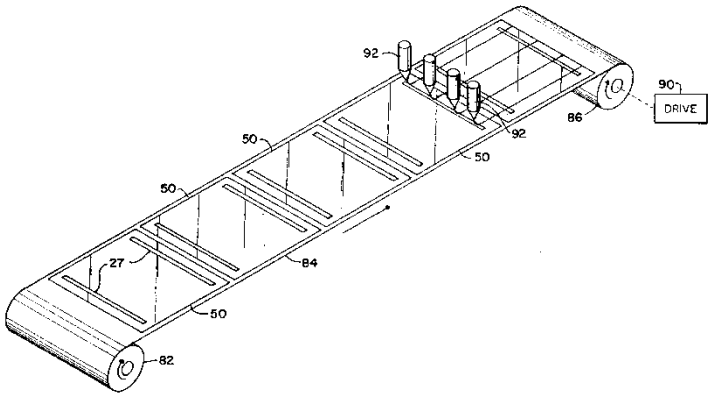
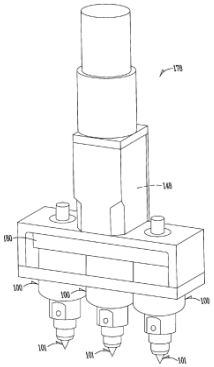
How can we achieve 24/7 production at 1400 - 2000 wafers/h?

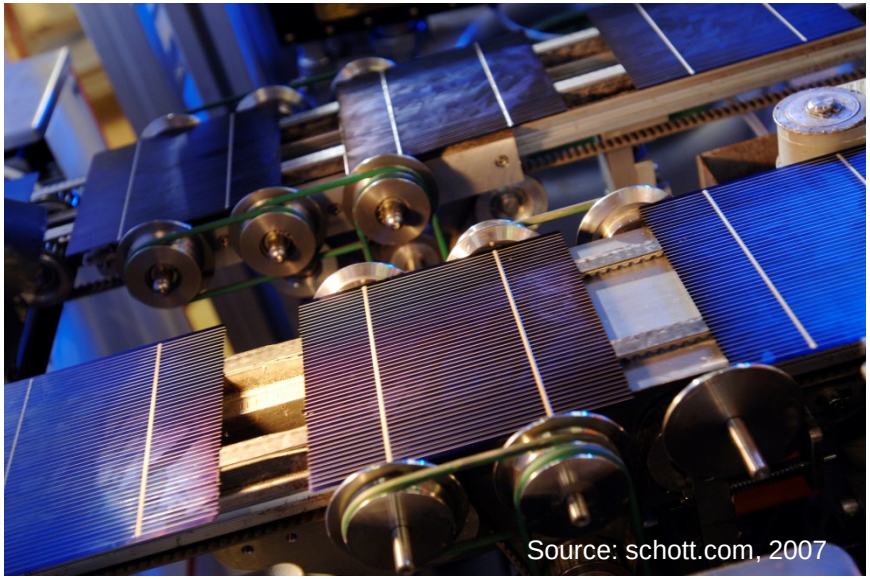
Parallel Dispensing Technologies

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-scrypt smart pumps [2,3]





Former solar cell production at Schott Solar AG

1) J. I. Hanoka, US005151377A (1992)

2) K. H. Church *et al.* *US*2010/0055299A1

3) X. B. Chen *et al.*, 37th IEEE-PVSC 2011

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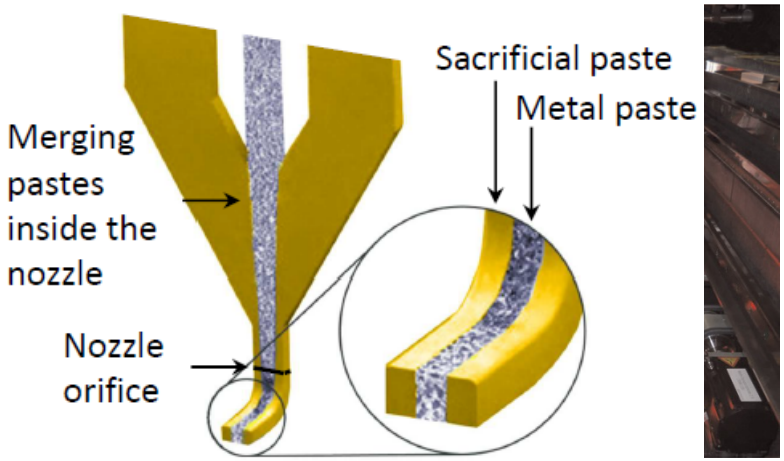
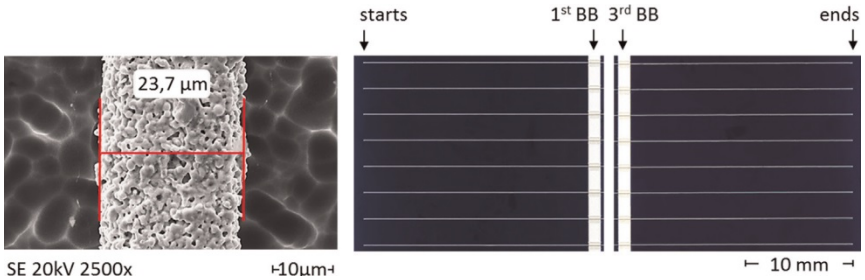
Parallel Dispensing Technologies
Co-Extrusion

- 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



Co-E [D. Fork, R. Rao, A. Lewis, S. Solberg; Palo Alto Research Center 2010]



Contact finger with precise line end positioning

1) M. Beutel *et al.*, SolMat **131**, 64 (2014).

2) L. P. Richter *et al.*, SolMat **142**, 18 (2015).

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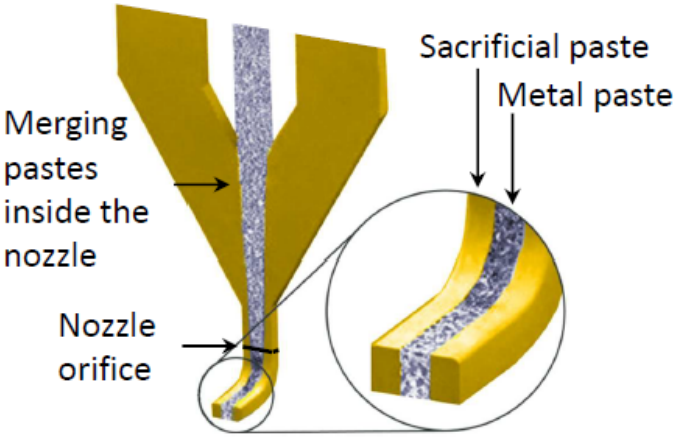
Fine Line Metallization by Dispensing / Extrusion
Dispensing vs. Co-Extrusion

Similarities:

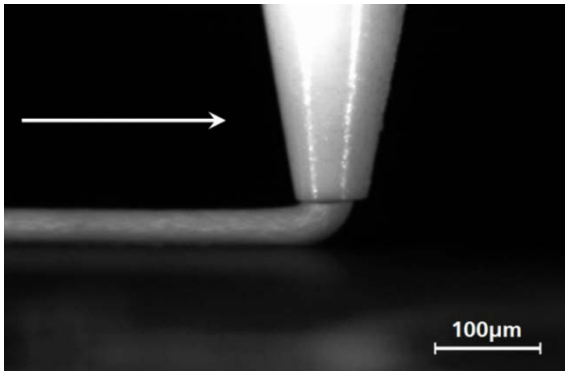
- Non-Contacting approach
- Homogeneous, high AR
- Parallel Print head developed
- Sinter contact formation [1)]

Differences:

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



[D. Fork, R. Rao, A. Lewis, S. Solberg; Palo Alto Research Center 2010]



[1)] Beutel, Silicon PV 2014

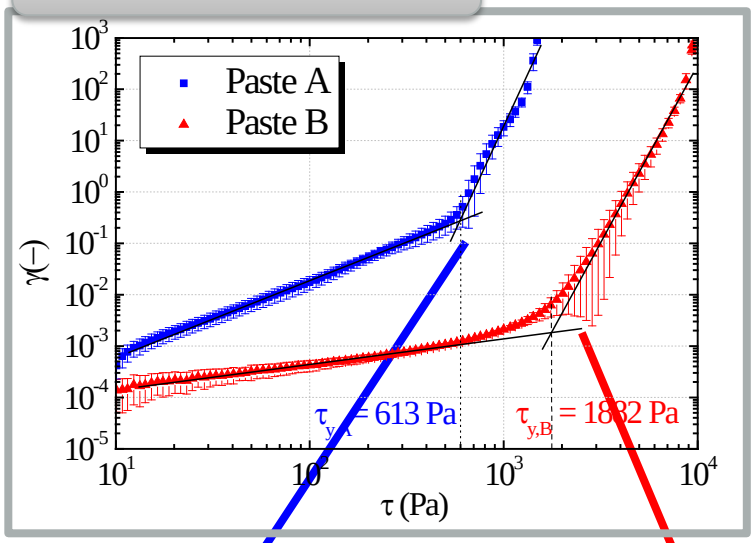
[2)] Reinhardt, AERC 2014

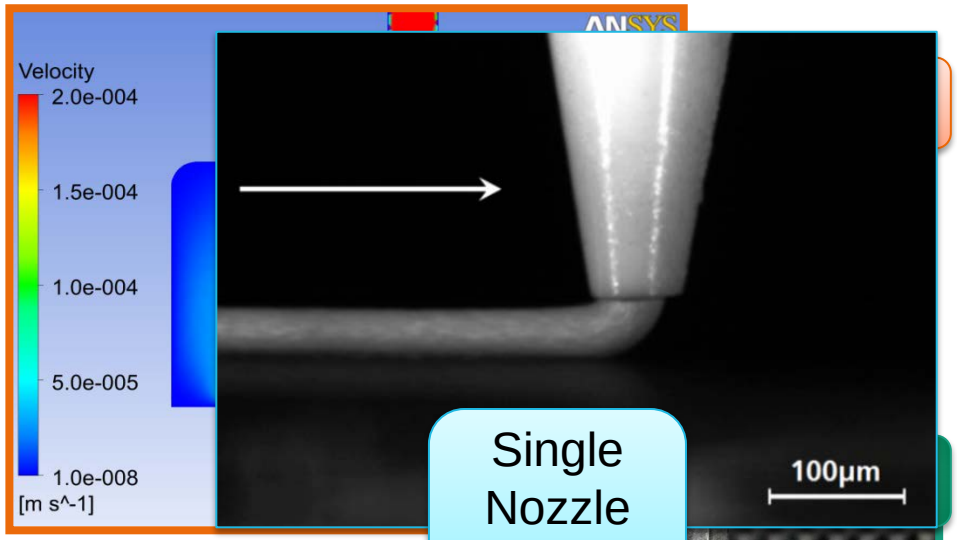
… and our way …

Dispensing at Fraunhofer ISE

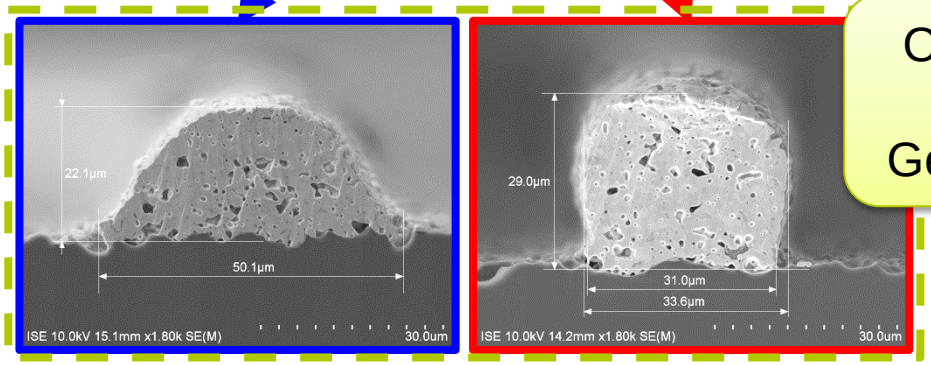
Development of Multi Nozzle Print Heads

Ag-Paste Rheology

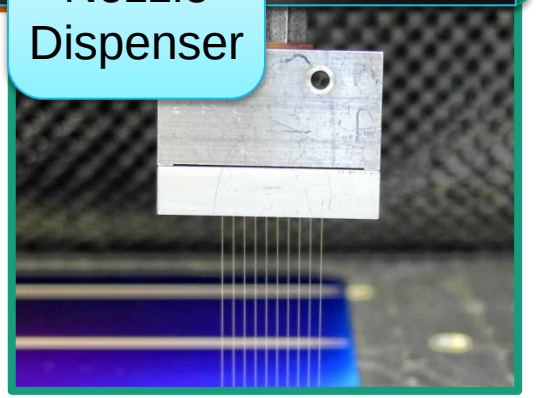




Single Nozzle Dispenser



Optimized Finger Geometries



12 Pospischil *et al.*, E. Proc. **43**, 111 (2013).

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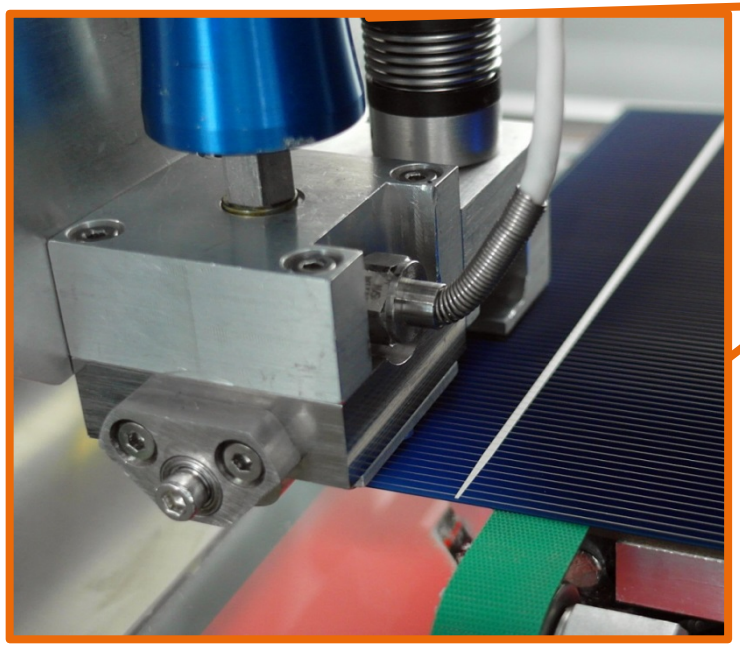
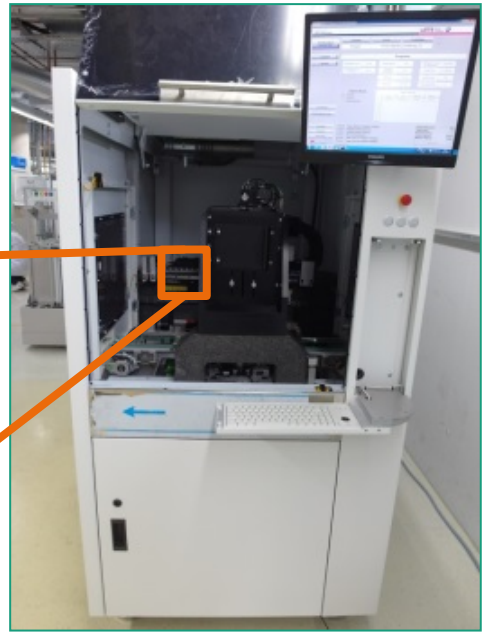
Dispensing as Industrial Metallization Process
Status Quo

Multi Nozzle Print Head

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





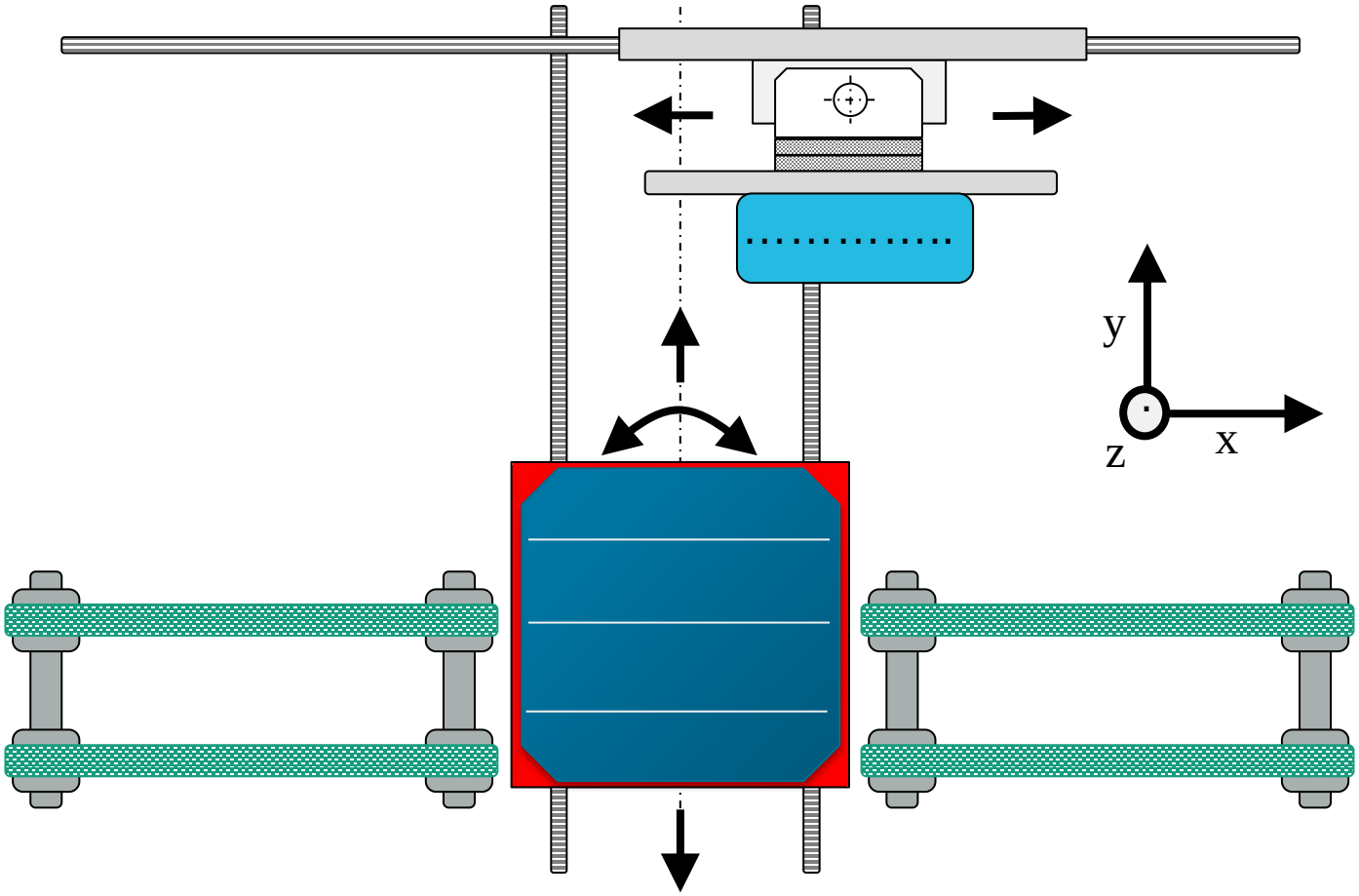
ASYS – Dispensing Platform

- Inline feasible dispensing platform
- High alignment precision

 Pospischil et al., E. Proc. **67**, 138 (2015).

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

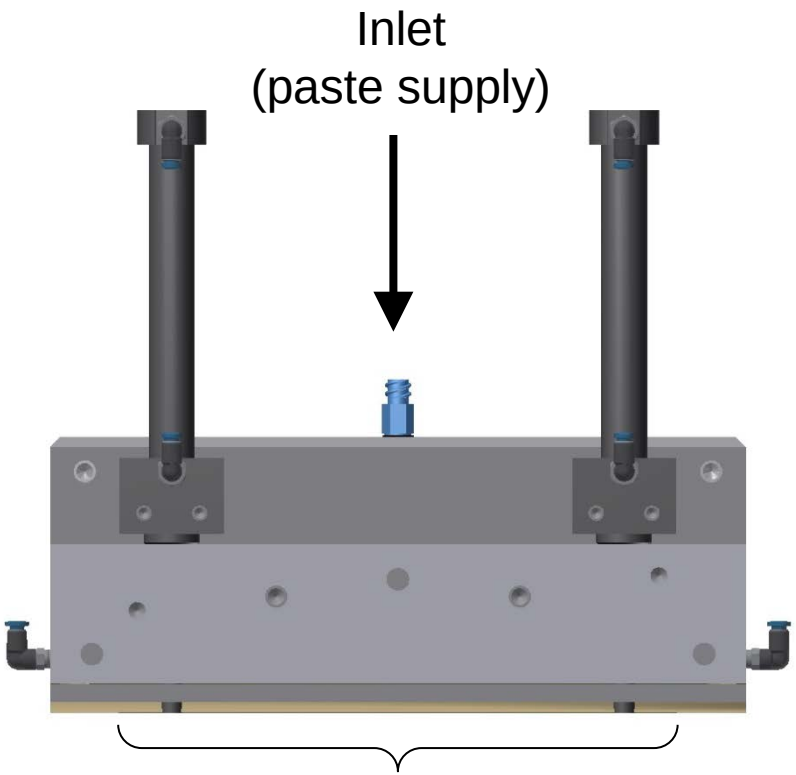
The Novel 6“ Dispensing Print Head
Close-up View

- Diameter of inlet
  - D_{in} = 2mm
- Slot width
  - w_s = 160 mm
- Interior paste volume
  - V ~18 cm³

x 80

- Current nozzle configurations

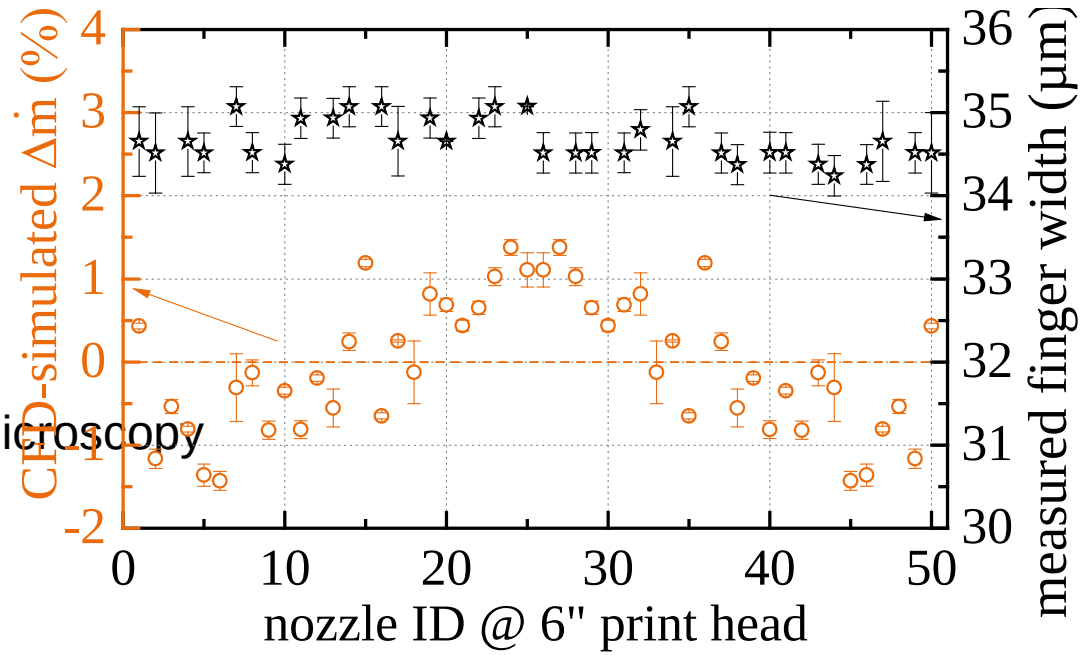
D	40µm	50µm	60µm
n	55	50	45



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)



Lateral deviation of simulated massflowrate and measured finger width on 6“wafer.

Results

- Contact geometry: **w_f=35±1µm @ AR~0.5**

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

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 °C, sunny side up

IV – Characterization

	FF (%)	*J_{sc} (mA/cm²)*	*V_{oc} (mV)*	*η (%)*
Best	80.1	40.3	659	**21.2**
Median	79.3	40.2	657	21.0

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

→ Process optimization ongoing

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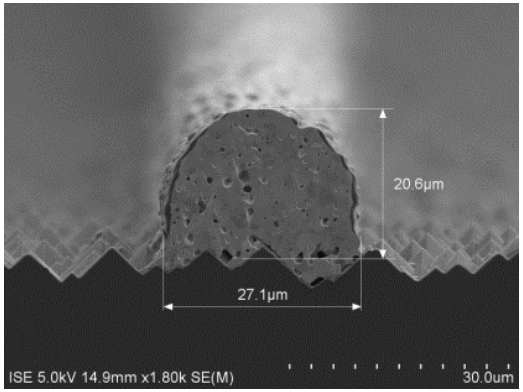
Summary
Novel 6“ print head launched



- 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 **~35±1µm @ AR~0.5**
- Max. efficiency achieved on industrial Cz-PERC: **η = 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

$$\tau_y \gg K\dot{\gamma}^n$$

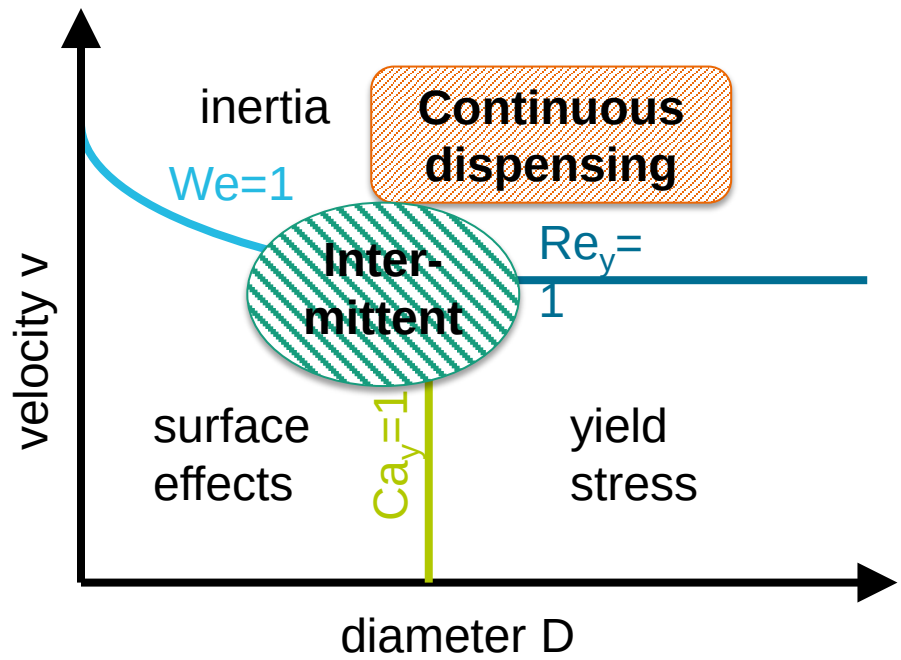
- Depending on operating conditions and rheology, inertia, surface or yield forces dominate
- Critical transition point:
  - D_c ~ 32 - 99µm
  - v_c ~ 350 - 583 mm/s

→ **Has to be dealt with during intermittent dispensing!**

$$Re_y = \frac{\rho \cdot \bar{u}^2}{\tau_y}$$

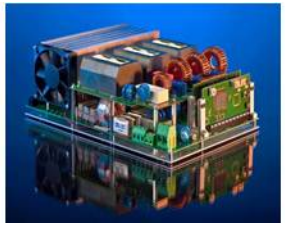
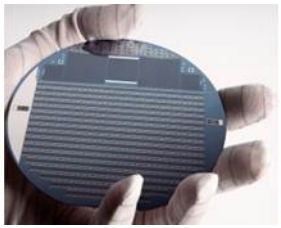
$$Ca_y = \frac{\tau_y \cdot D}{2\sigma}$$

$$We = \frac{\rho \cdot \bar{u}^2 \cdot D}{2\sigma}$$



Thank you for your attention!




… and all Co-authors and Co-workers within the Dispensing Project

… as well as our industry partners:

ASYS SOLAR Heraeus

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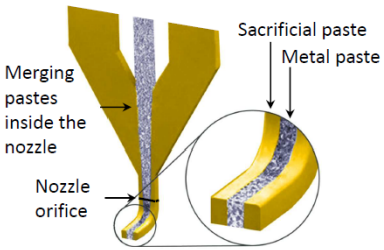
ASYS SOLAR Heraeus Fraunhofer ISE

APPENDIX

Parallel Dispensing Technologies
Co-Extrusion



[D. Fork, R. Rao, A. Lewis, S. Solberg; Palo Alto Research Center 2010]

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- 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,
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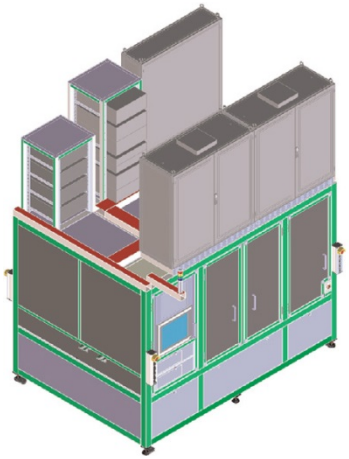
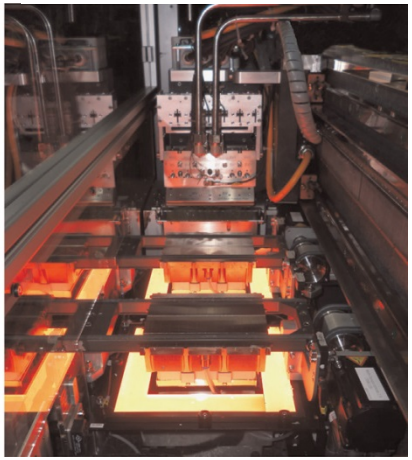
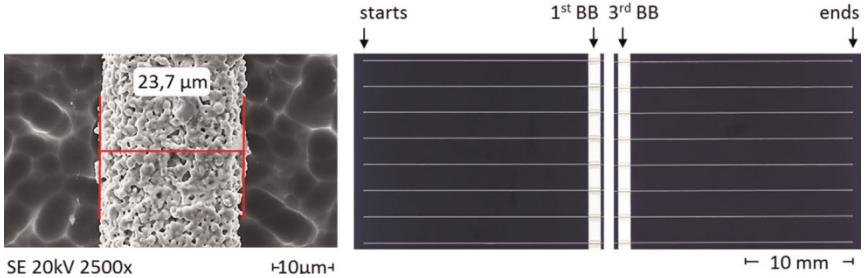




Co-Extrusion production tool with print head



Contact finger with precise line end positioning

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Influences of Rheology

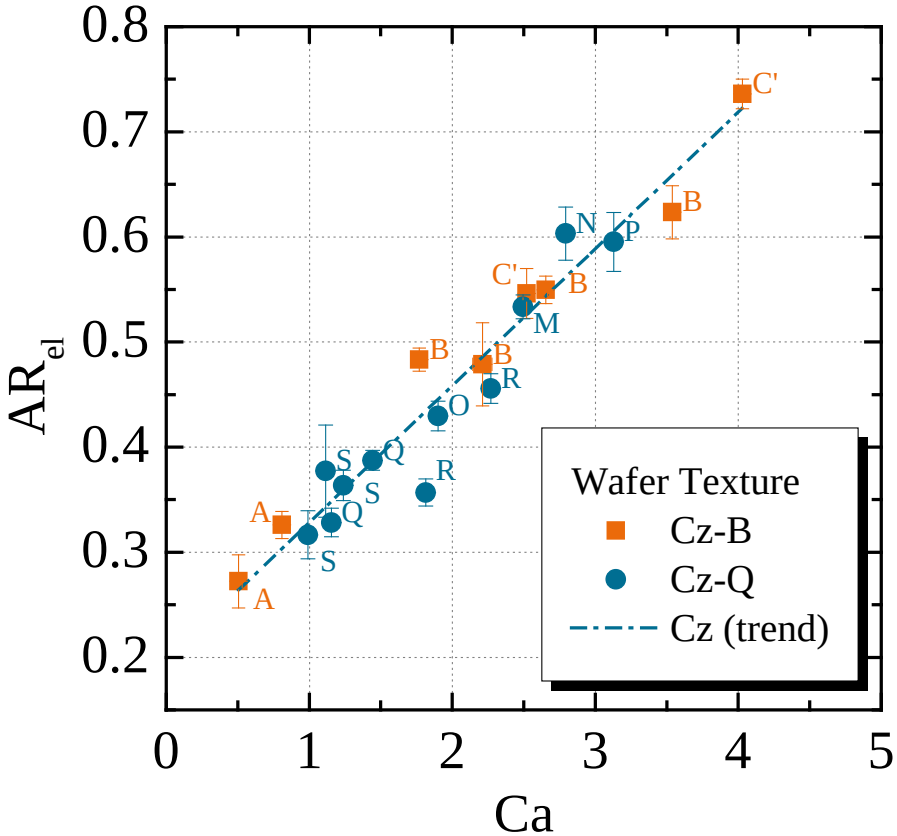
How to reach higher Aspect Ratios

$$Ca = \frac{\tau_y \cdot D}{2\sigma} = \frac{viscous\ stresses}{surface\ tension}$$

- τ_y (kPa): yield stress
- D (μm): nozzle diameter
- Γ $\left(\frac{mN}{m}\right)$: surface tension

- **AR_{el}** linear dependent on capillary number **Ca**
- Minimum on Cz: $AR_{el} \xrightarrow{Ca=0} 0.2$

→ **Decrease of D requires adaptation of rheology**



Aspect Ratio depending on Capillary number.

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- τ_y (kPa): yield stress
- D (μm): nozzle diameter
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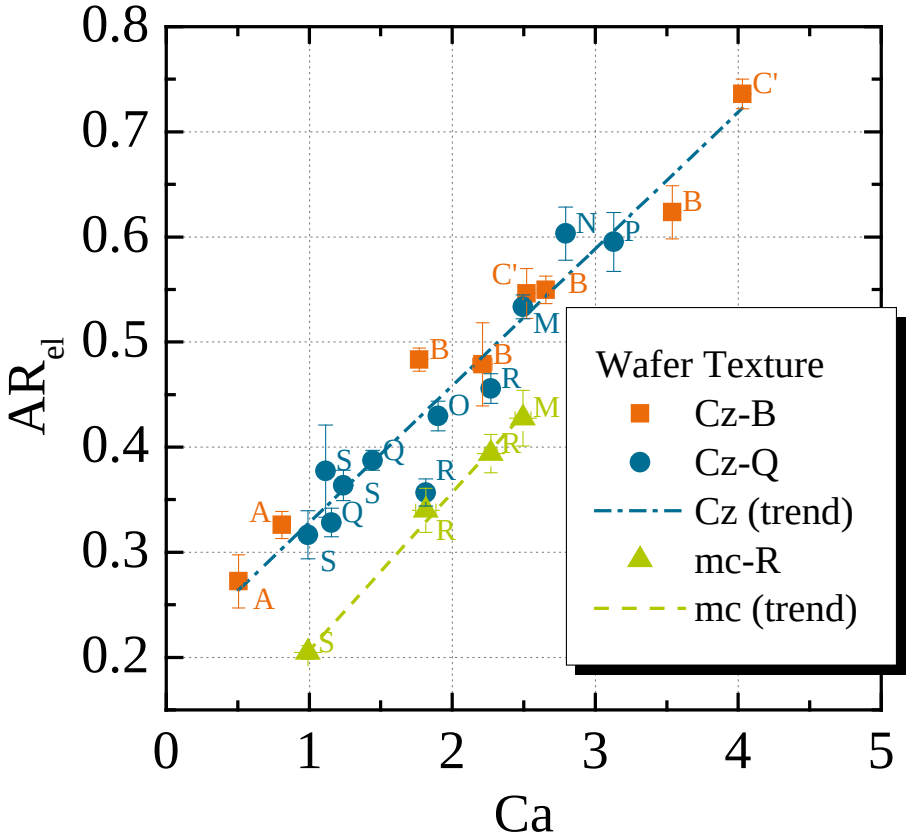
→ **Decrease of D requires adaptation of rheology**

→ **Consider influence of wafer surface**



Aspect Ratio depending on Capillary number.

Rheological Characterization of Printing Pastes

Analysing flow curves

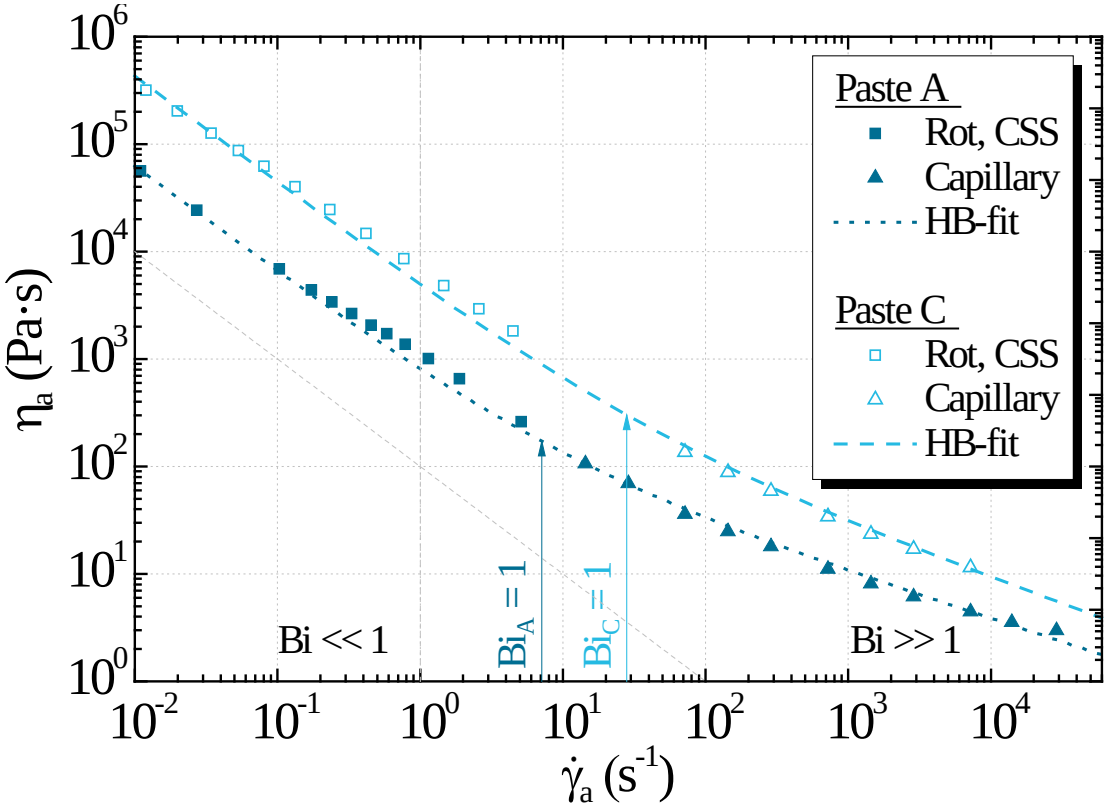
- Herschel-Bulkley

$$\eta = \frac{\tau_y}{\dot{\gamma}} + K\dot{\gamma}^{n-1}$$

- Influence of yield stress dominates at low shear rates

$$\mathbf{Bi} = \frac{\tau_y}{K\dot{\gamma}^n} \gg 1$$

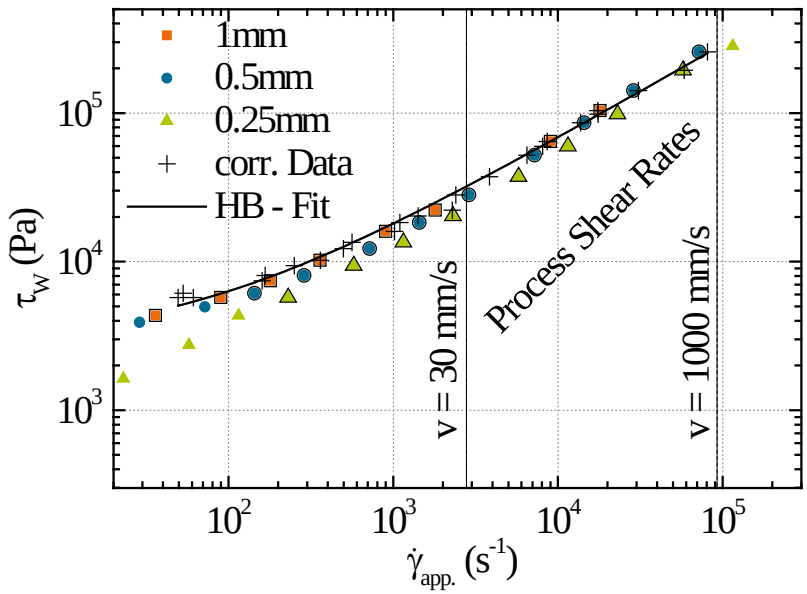
- Rotational rheometers with limited applicability
- Capillary devices required for correct interpretation



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.

Pospischil, M., Diss. to be published

Characterization of Capillary Flow

Mooney Analysis - Determination of wall slip

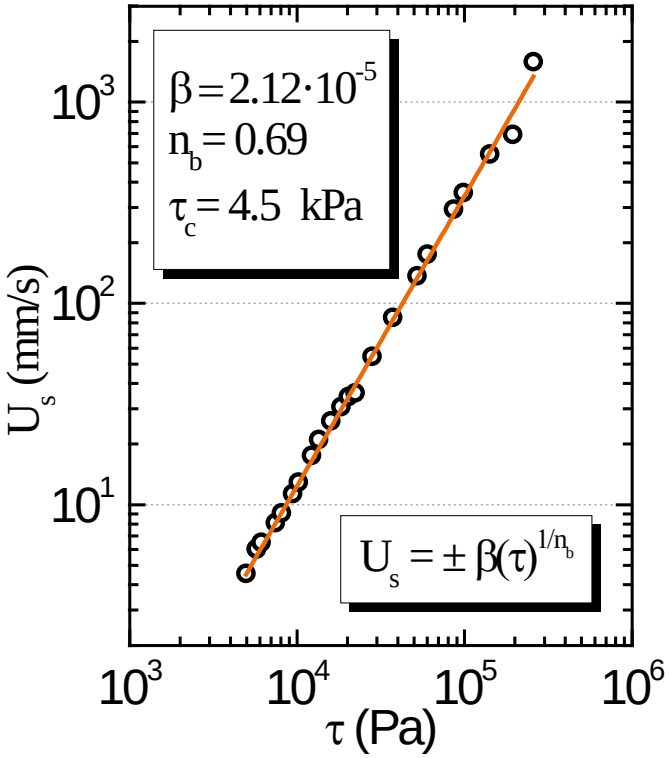
Data Analysis

- 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.)

Pospischil, M., Diss. to be published