Highspeed Video Analysis of The Paste Transfer Process During Screen Printing

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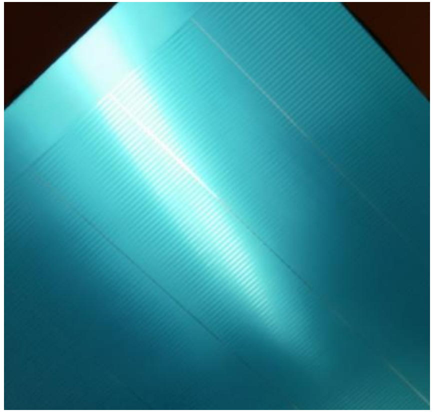

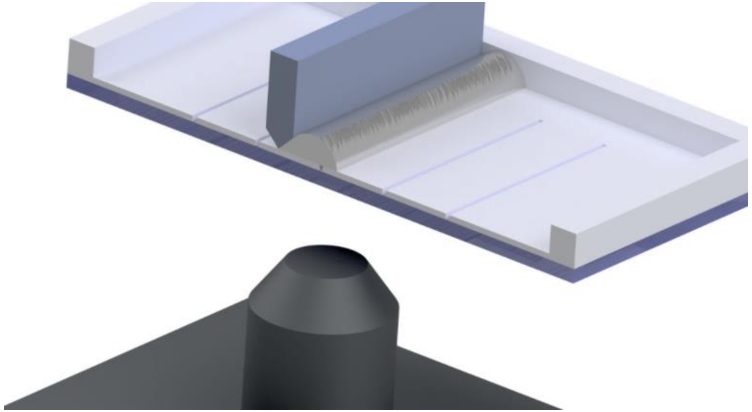

Reasons for a Highspeed Video Analysis During Printing

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- Ever narrower metallization lines demand improved paste formulation

- Screen printing process and paste rheology demands are not fully identified
  - Process modeling is still based on theories from the 1980‘s

    Riemer, DE, “The Theoretical Fundamentals of the Screen Printing Process.” Microelectron. Int., (1989)
    Messerschmitt, E, “Rheological Considerations for Screen Printing Inks.” Screen Print., (1982)

  - Newer studies mainly apply a black box approach

- Highspeed video imaging allows for a in situ analysis of the process
  - formation of typical defects is observable in slow motion
  - Relevant rheological and wetting properties for screen printing can be retrieved

How the Final Line Width in Screen Printing is Formed

The presented study analyzes the mechanism of paste spreading during printing fundamentally for two pastes differing in their rheological properties

- Open Questions
  - When exactly does spreading take place?
  - What is the driving force for spreading?

- Approach
  - Theoretical consideration about spreading due to gravity
  - Evaluation of different printing parameters
  - Compare different metallization pastes
    non-volatile free capillary suspension vs commercial paste including polymeric additives

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Capillary Suspension Type Pastes

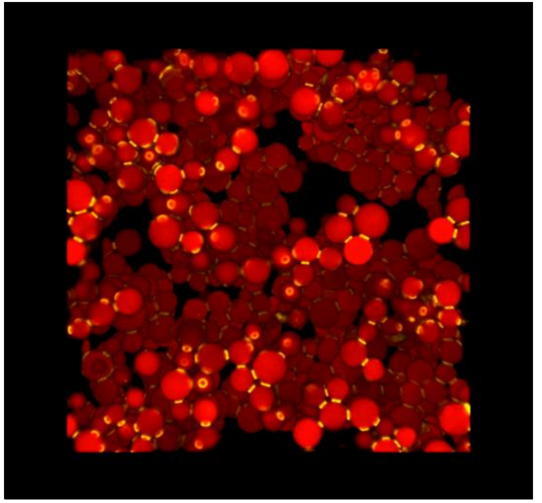
- Alternative formulation approach abandoning non-volatile ingredients
  - Impurity free lines after sintering promote conductivity
  - Efficiencies 0.1% below commercial reference reached

C. Yüce, K. Okamoto, L. Karpowich, A. Adrian, and N. Willenbacher, "Non-volatile free silver paste formulation for front-side metallization of silicon solar cells," Sol. Energy Mater. Sol. Cells, (2019)

- Rheology adjustment via capillary forces creating a percolating particle network

Koos and Willenbacher, „Capillary forces in suspension rheology", Science (2011)

Pendular State Particle Network



Bossler and Koos, „Structure of Particle Networks in Capillary Suspensions with Wetting and Nonwetting Fluids", Langmuir (2016)

Metallization Paste Properties I

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Two pastes differing in their rheological properties are studied

	Capillary Suspension	Commercial reference
Solid fraction	91 ± 1 wt.%	90 ± 1 wt.%
Secondary fluid volume	5%	-
Paste density	5.3 g/cm3	5.7 g/cm3
Apparent yield stress σ_y	858 ± 29 Pa	513 ± 63 Pa
Viscosity (extrapolated at 500 s^{-1}) η	12 ± 1 Pa S	21 ± 2 Pa S

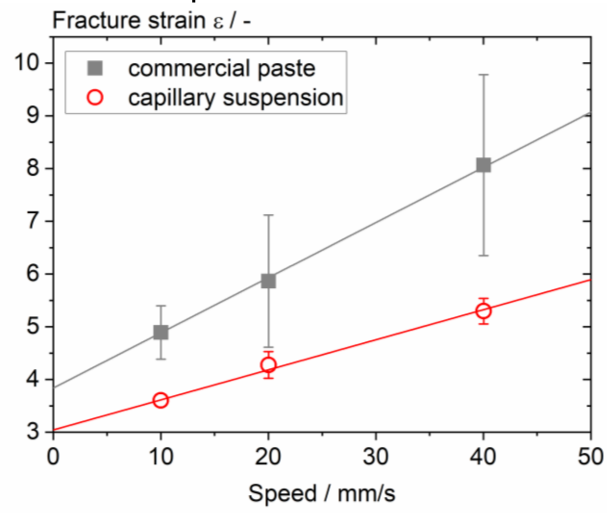
Commercial paste is characterized by an elevated high - shear viscosity and lower apparent yield stress

K. Abdel Aal, N. Willenbacher, Front side metallization of silicon solar cells – A high-speed video imaging analysis of the screen printing process, Sol. Energy Mater. Sol. Cells. (2020)

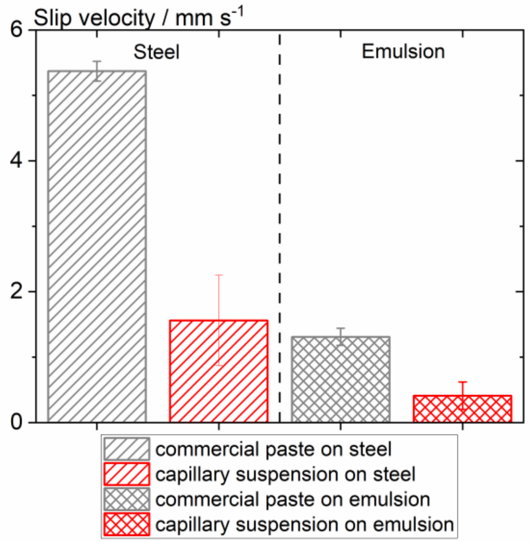
Metallization Paste Properties II

Two pastes differing in their cohesive and slip properties are studied

Paste fracture strain in uniaxial extension as measure for paste cohesion



Slip velocities for different pastes



@ 800 Pa shear stress

Commercial paste is characterized by a higher cohesive strength and more slip

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Is Sagging Due to Gravity After Printing Realistic ?

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Hydrostatic pressure: $p = \rho * g * H$

Paste density: $\rho = 5.7 \frac{g}{cm^3}$ gravitational acceleration: $g = 9.81 \frac{m}{s^2}$

→ Hydrostatic pressure: $p = 5.7 \frac{g}{cm^3} * 9.81 \frac{m}{s^2} * 60\mu m$

Estimated pressure prevalent in the bottom layer of a printed finger line

$$p = 3\ Pa$$

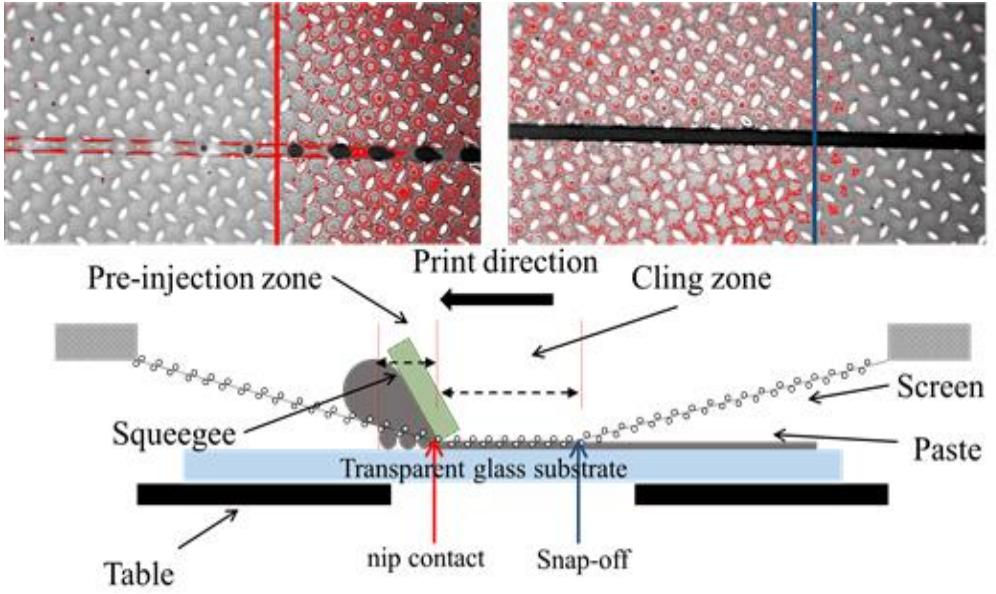
Yield stress – the transition point from elastic solid behavior to viscous flow

$$\sigma_{y,commercial} = 513 \pm 63\ Pa$$

What is the reason for spreading?

Highspeed Video Imaging During Screen Printing

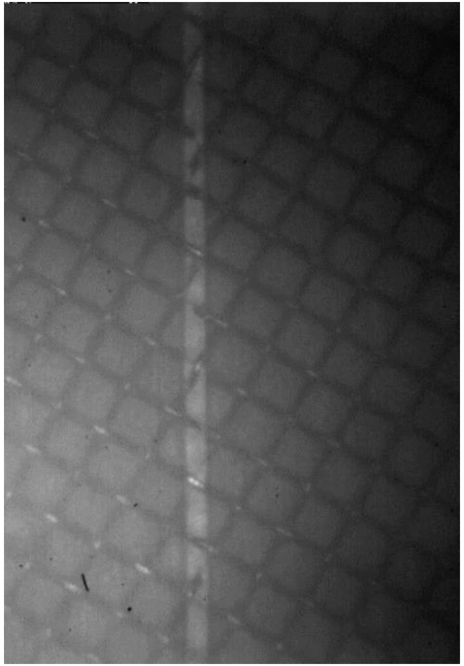
- A highspeed camera allows capturing the process steps at 1000 frames per second during printing



Xu and Willenbacher, Journal of Coating Technology and Research (2018)

Screen Printing of a Commercial Metallization Paste

Commercial Paste



Snap off 1.5 mm | Printing speed 200 mm/s | Pressure 74 N/cm | Diamond Squeegee

- Emulsion sealing visible by refraction pattern
- Pre-injection visible by dark dots
- Spreading during squeegee contact
- Retraction during snap-off process

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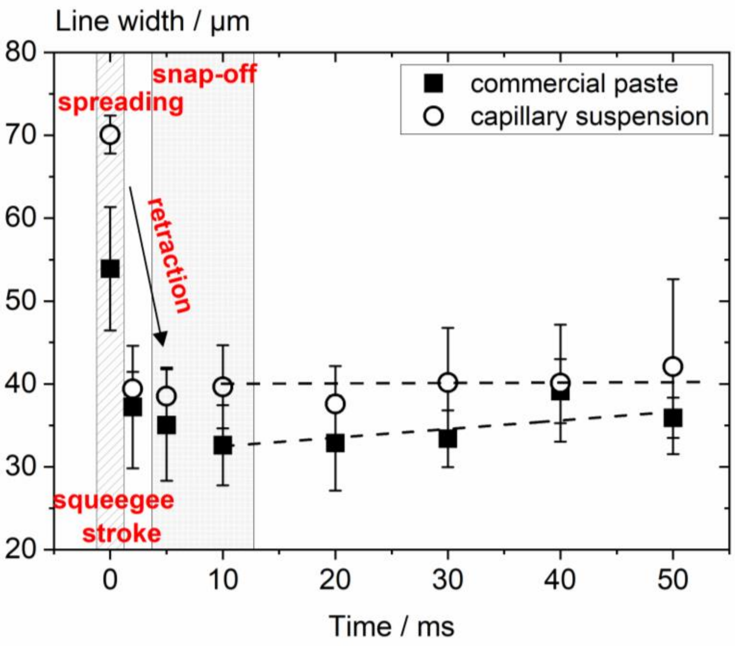
Line Spreading During Printing

- Line spreading and retraction is a feature of the screen printing process
- The phenomenon is differently pronounced for different metallization pastes
- The line width is essentially set when the screen detaches from the substrate



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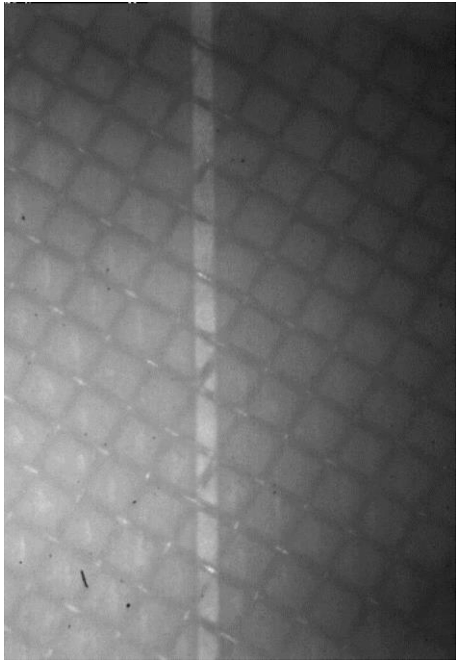
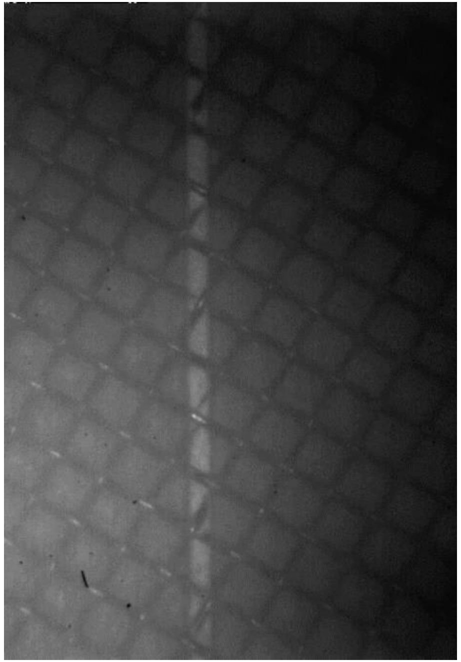
Printing with an Extended Cling Zone

- Continuous spreading during cling period
- Retraction during snap-off process
- Spreading higher for paste showing
  better wetting,
  lower viscosity and cohesion,
  but higher yield stress

Capillary Suspension



Commercial Paste



Snap off 0.5 mm | Printing speed 300 mm/s | Pressure 74 N/cm | Diamond Squeegee

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Evolution of Line Width with Extended Cling Zone

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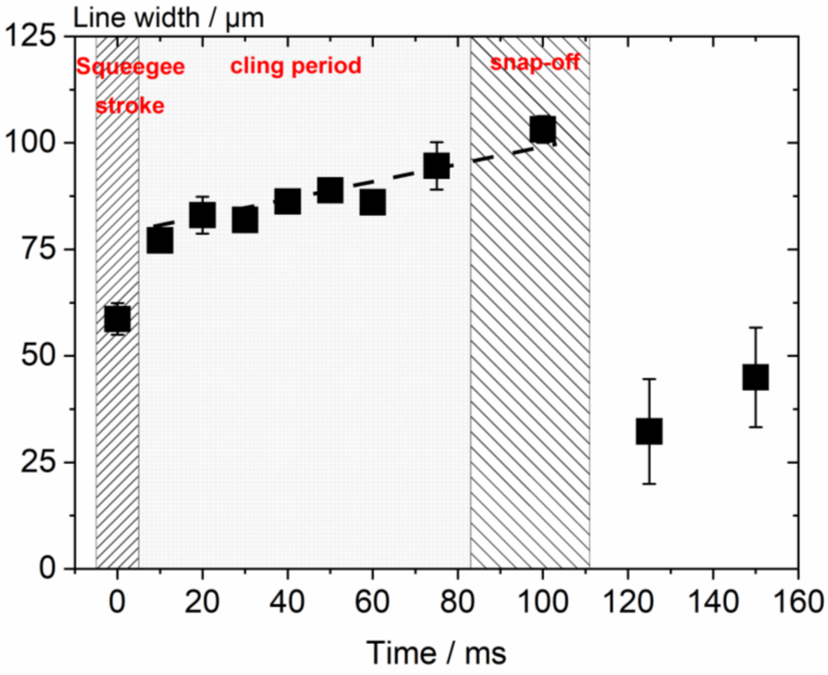
Evolution of line width for the commercial paste

- Strong spreading during squeegee contact
- Linear spreading during lasting cling zone
- Retraction during the snap-off process



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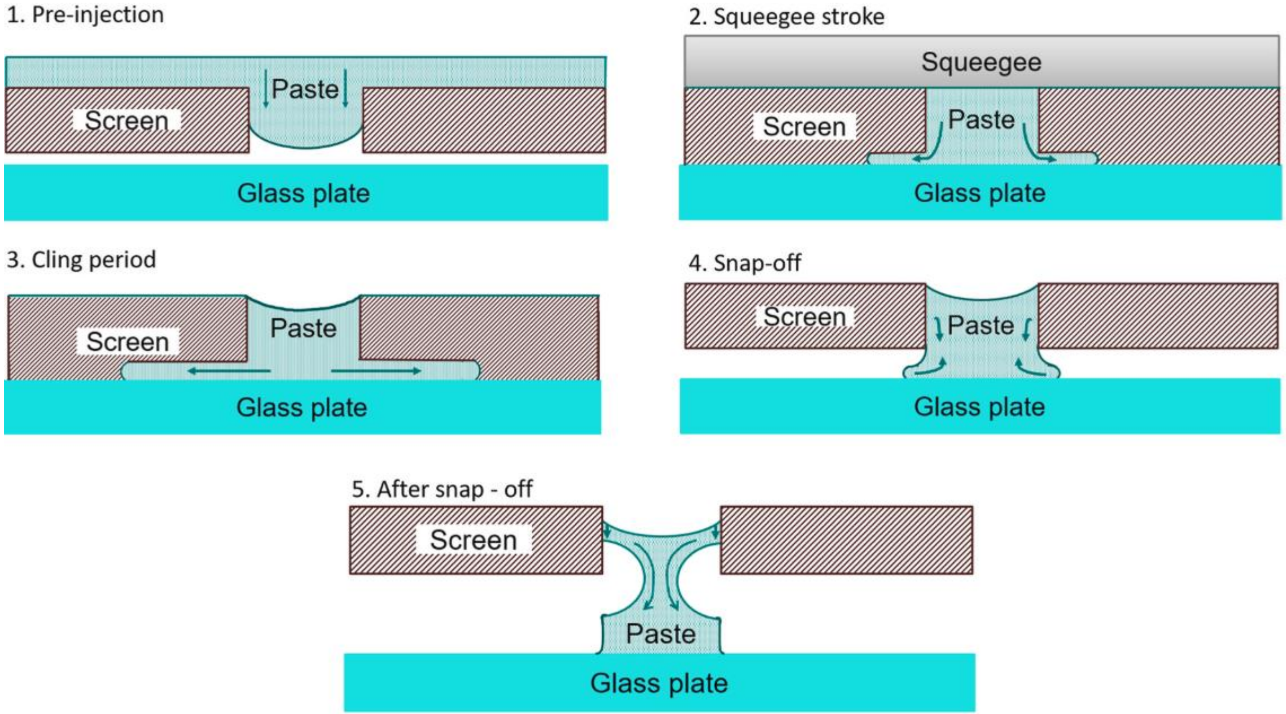
Proposed Mechanism for Paste Release



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Summary

- Spreading and retraction are fundamental phenomena during fine-line printing
- Paste gets further pulled in-between screen and substrate during cling period
- Amount of spreading higher for paste showing a better wetting, lower viscosity and cohesion, but higher yield stress
- Cohesive and slip properties of the paste control paste release from the screen
- Further experiments using paste formulations with independently varying wetting and rheological properties in progress

Thank You for Your Attention

Questions?

Acknowledgement:

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