Screen-printed metallization for industrial solar cells – current perspectives and future opportunities

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SERIS is a research institute at the National University of Singapore (NUS). SERIS is supported by NUS, the National Research Foundation Singapore (NRF), the Energy Market Authority of Singapore (EMA) and the Singapore Economic Development Board (EDB).

Outline

- Introduction
- Screen-Printing technology components
- Solar cell metallization
- Screen-Printing metallization system
  - Screen-printer
  - Screen
  - Pastes
- Challenges and opportunities
- Future outlook
- Summary

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Introduction – historical background

- Screen-printed metallisation of solar cells developed by Spectrolab, USA in 1975 [1]

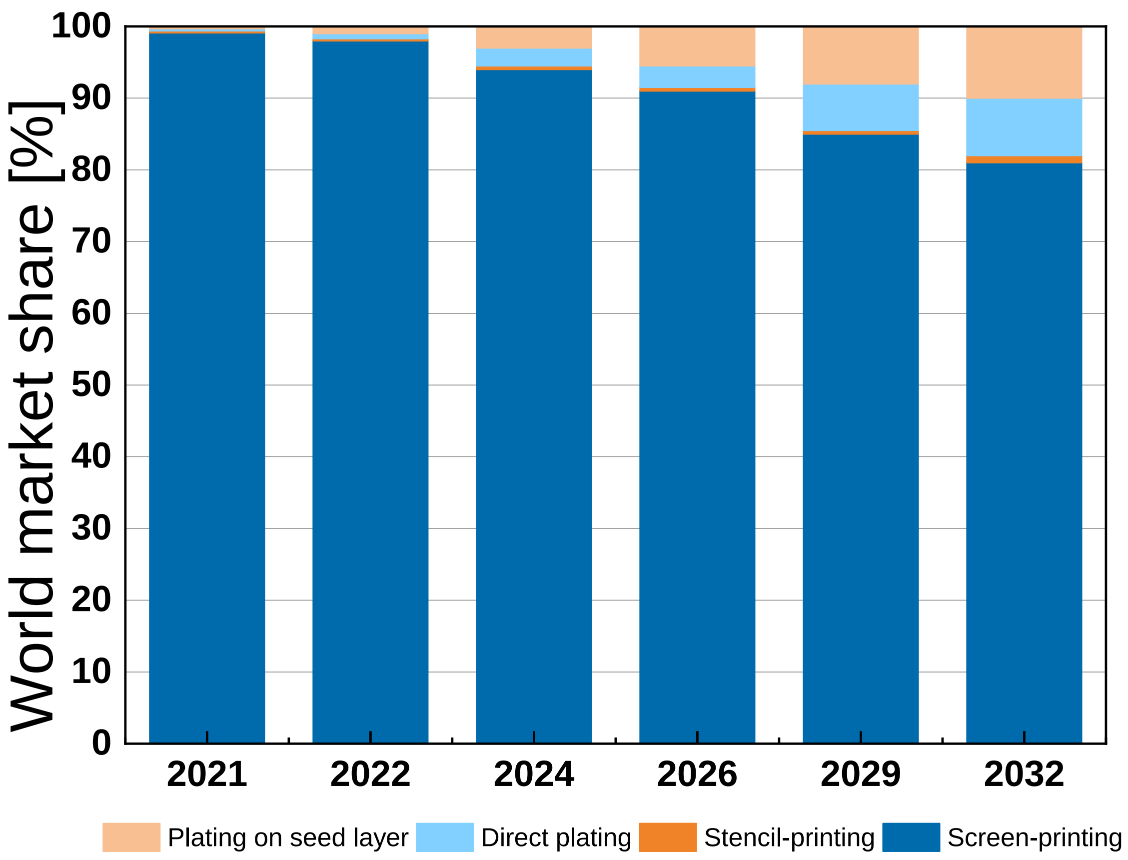
- Demonstrated efficiencies of 13% on mc-Si Al-BSF solar cells [2]

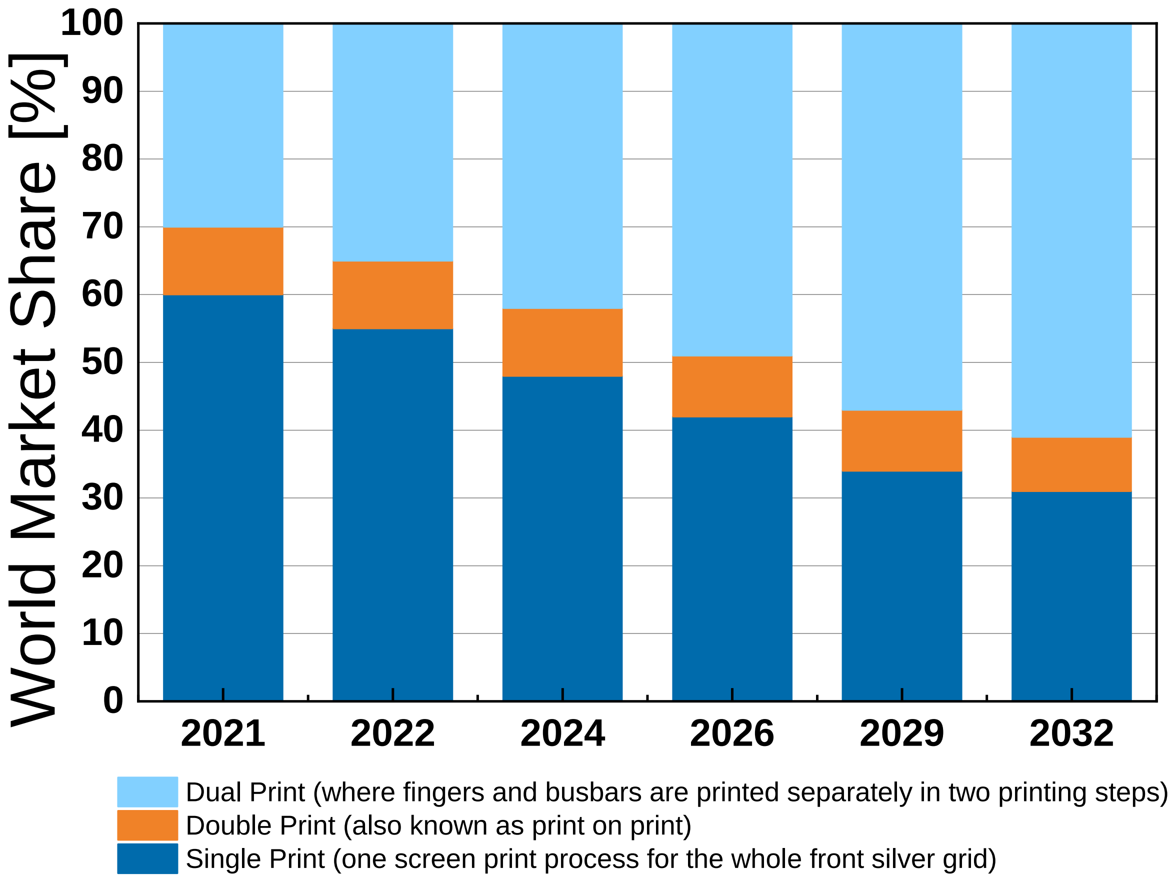
- Simple process, poor performance [2]
  - 150 µm wide, 10 µm thick, aspect ratio – 0.06
  - Paste conductivity ≈ 1/3 of Ag
  - High contact resistance due to glass frits

- Contribution to losses [2]
  - Shading losses – 10%
  - Resistive losses – 10%
  - Additional Jsc losses due to heavily diffused front surface – 10%

[1] Green MA, Jpn Journal of App. Physics, 2019
[2] Tepner S, PIP, 2023.

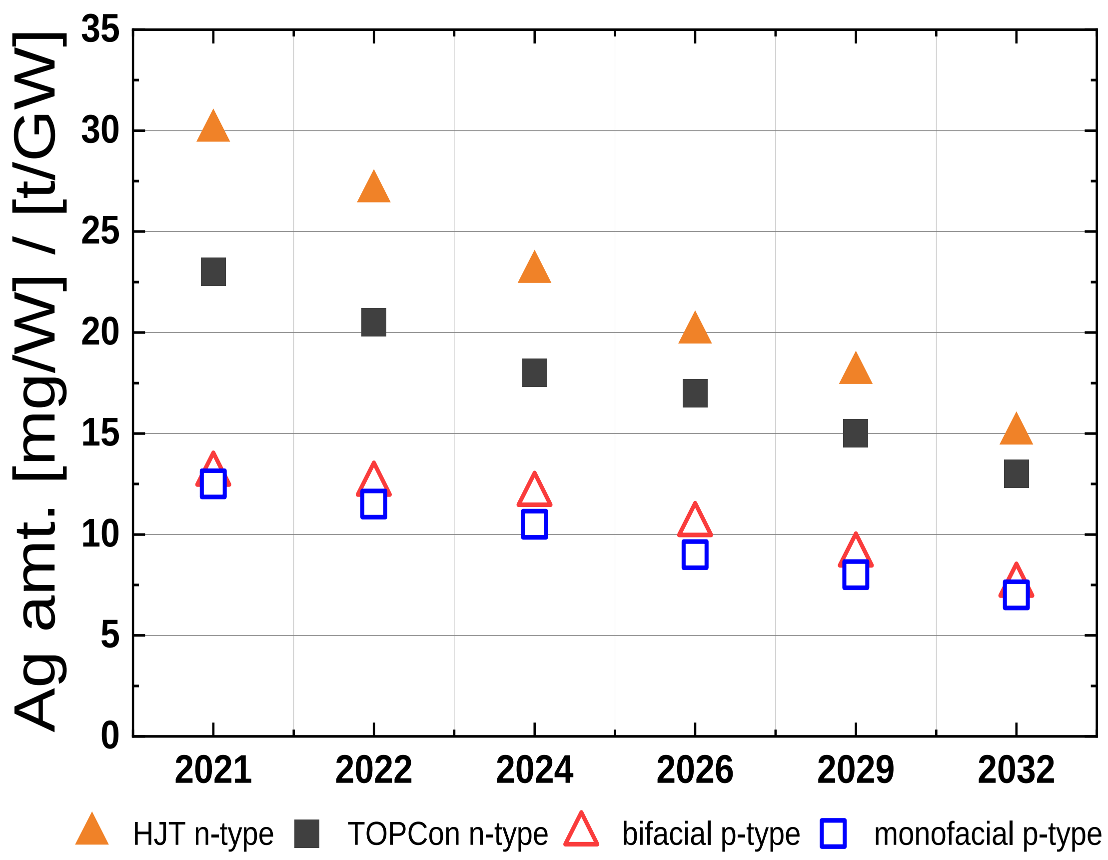
Introduction – Market status

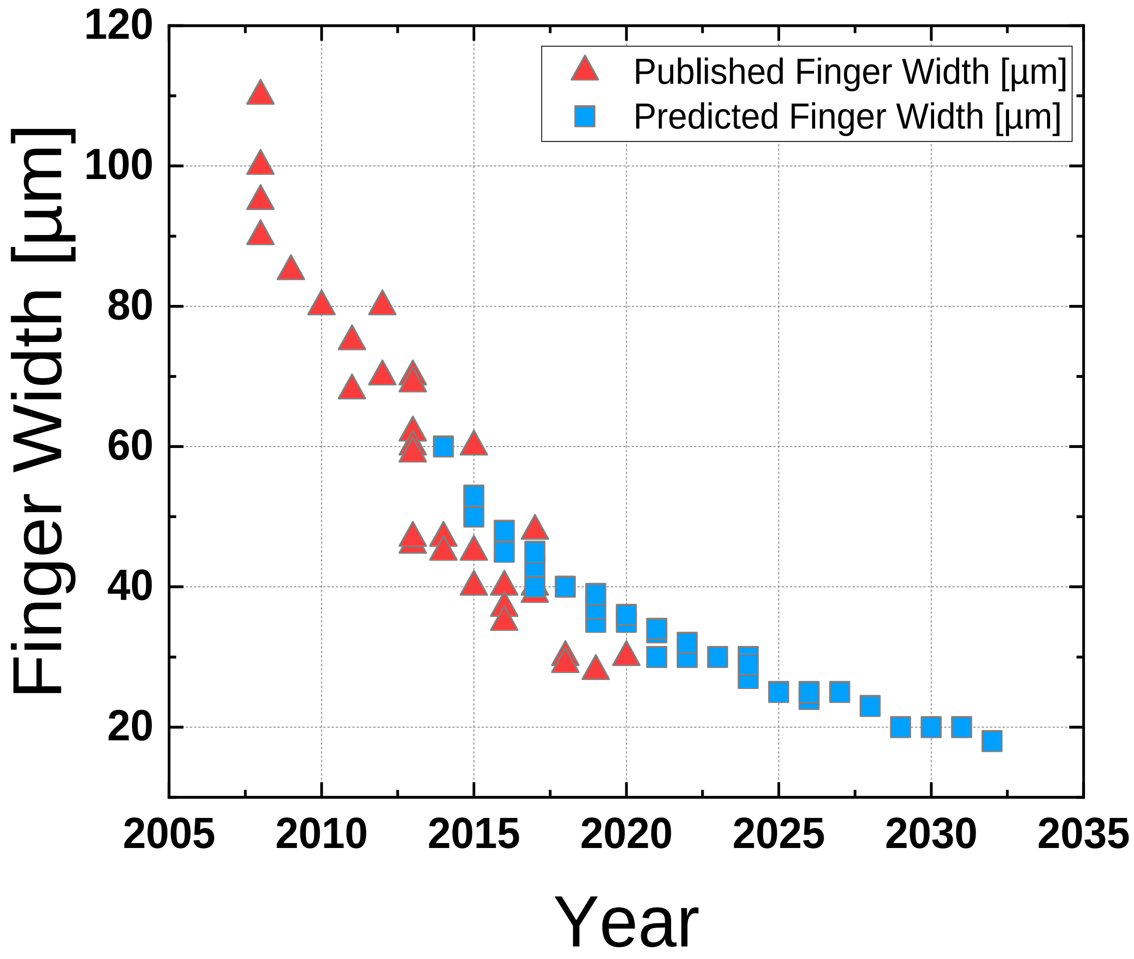




Data source: ITRPV 2022

Introduction – Ag consumption and finger width





Data source: ITRPV 2022 , Tepner S, PIP, 2023

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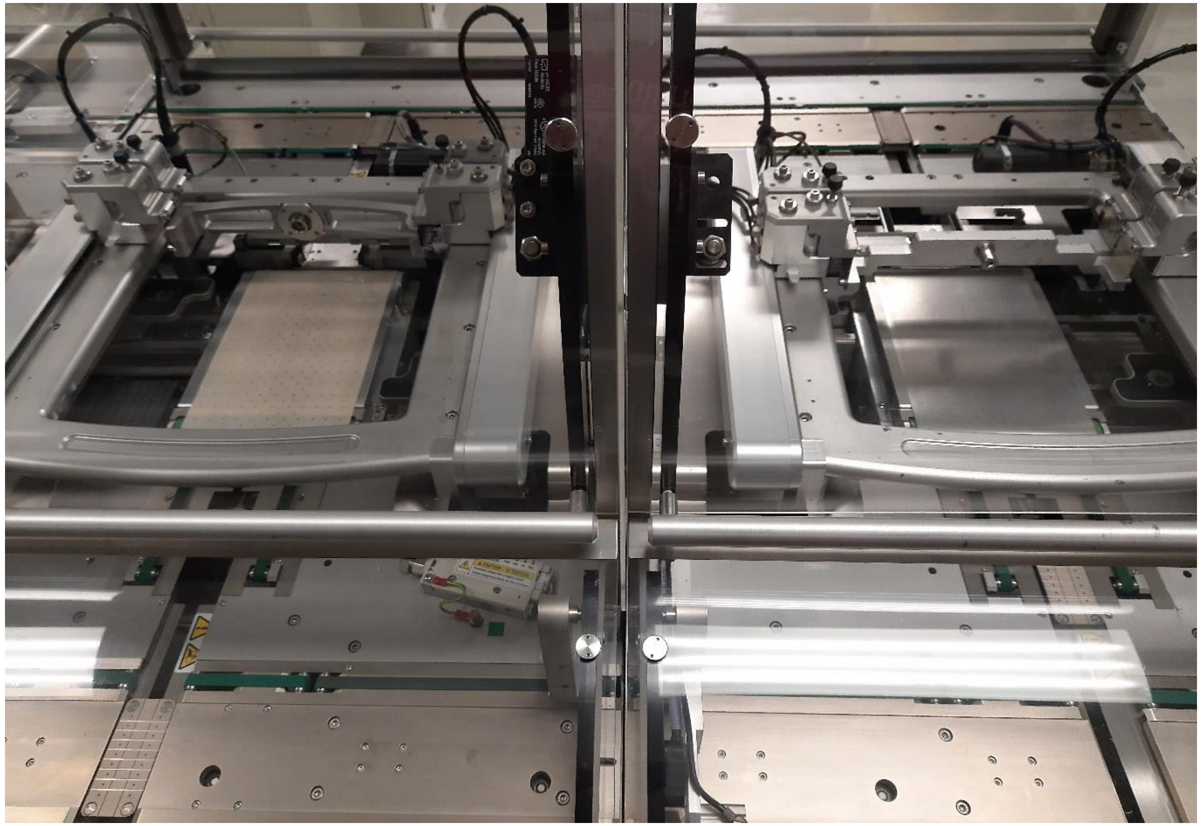
Screen-Printing technology components

Primary components

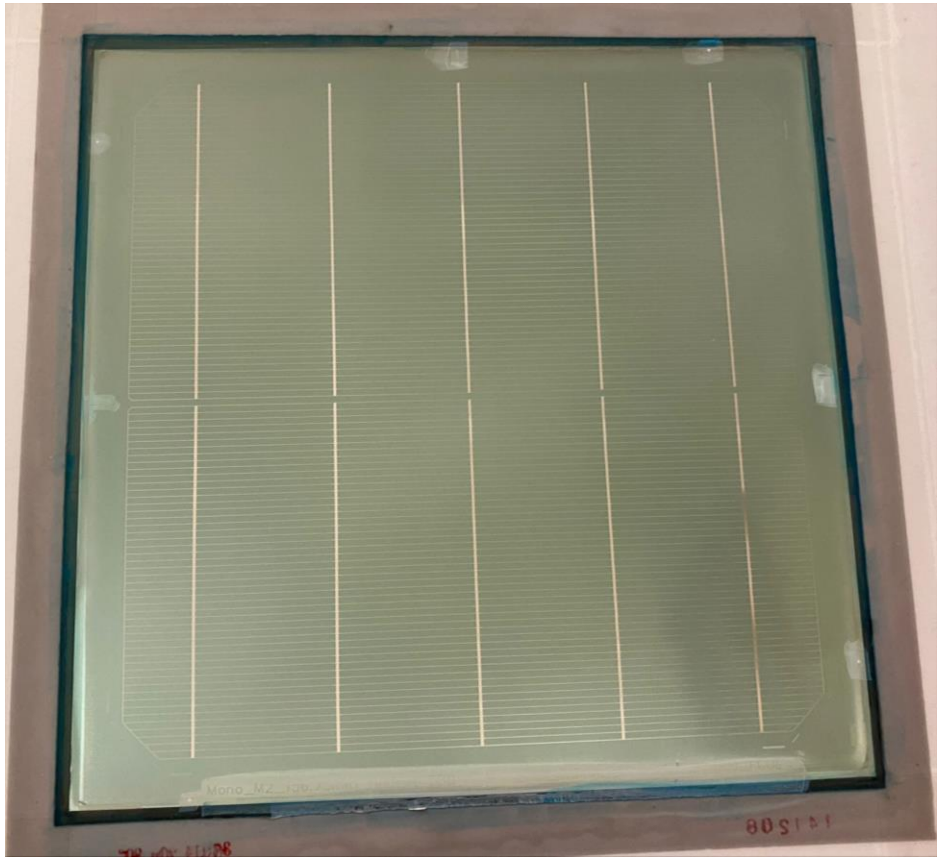


Screen-Print table/nest

Accessories

Screen-Printing technology components

Primary components

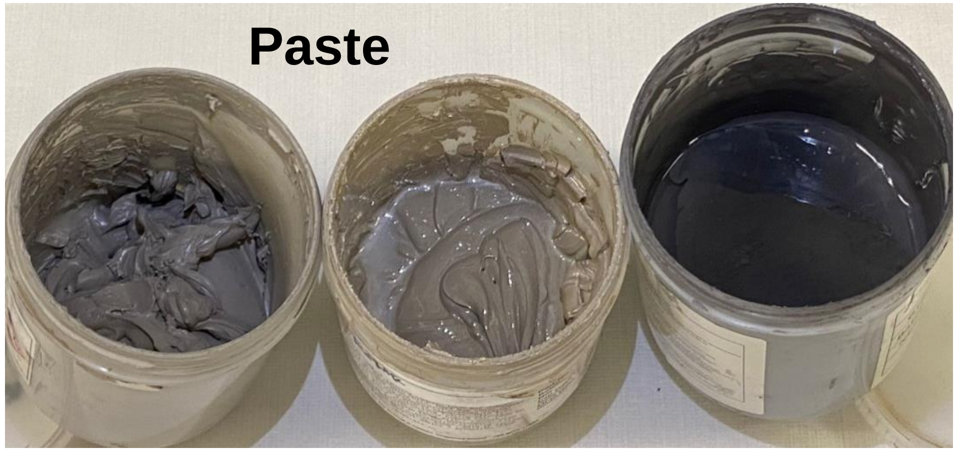


Screens

Screen rack

Screen-Printing technology components

Primary components



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Solar Cell Metallization - Requirements

- Minimal shading on the front side (monofacial/IBC/ABC) or both sides (for bifacial solar cells)
- Low lateral grid resistance
- Low contact resistance with the transport layer on the solar cell
- Low metal-related saturation density under the metal contacts
- Strong adhesion to the solar cell surface and to the interconnection ribbons/wires

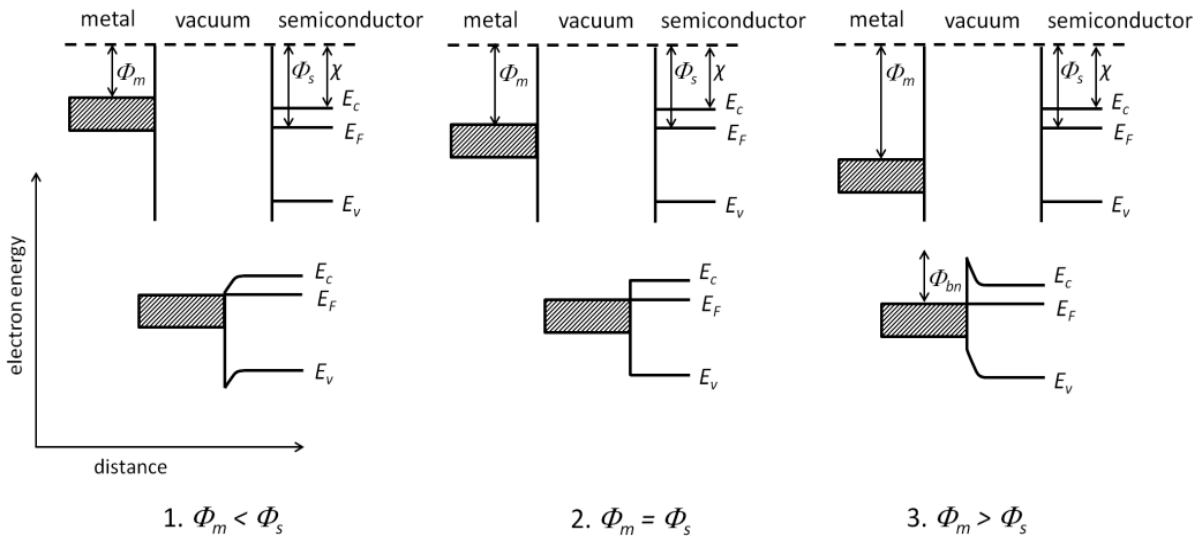
Solar Cell Metallization – Optimizing parameters

Parameter	Finger/BB Characteristics	Dependence
Optical Shading	shape, width, number	Paste, screen, methodology
Series resistance	Number, material	Rsheet, lateral transport, annealing temperature
Silver consumption	shape, width, number	Paste material, methodology
Interconnection compatibility	shape, width, number	Paste material, lateral transport, methodology
Metal induced recombination	Metal area fraction	Dopant distribution, paste, annealing/firing temperature

Finger cross-section	Technology
Triangular	String Printing
Circular	Dispensing, plating
Gaussian	Screen Printing (flatbed, rotary)
Quadrilateral	PVD, evaporation

Solar Cell Metallization – Basic Theory

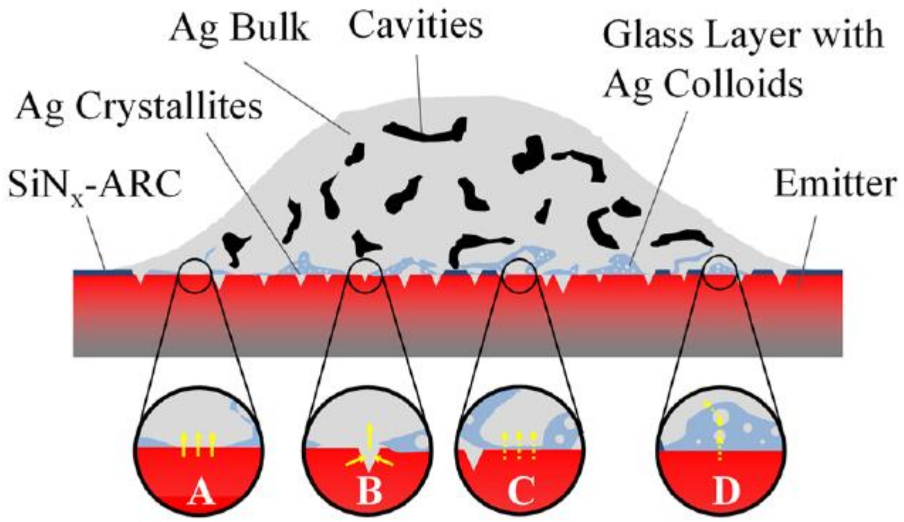
Metal Semiconductor contact [1]



For n-type semiconductor -

1. $\Phi_m < \Phi_s$: Accumulation contact
2. $\Phi_m = \Phi_s$: Neutral contact
3. $\Phi_m > \Phi_s$: Depletion contact

Charge carrier transport [2]



A. Direct contact between bulk metal-SC
B. Metal crystallites on SC surface
C. Tunnelling through interfacial glass layer (FT pastes)
D. Multi-step tunnelling through metallized glass layer

[1] D. Schroder, Semiconductor Material and Device Characterization, 2006
[2] Tepner S, PIP, 2023.

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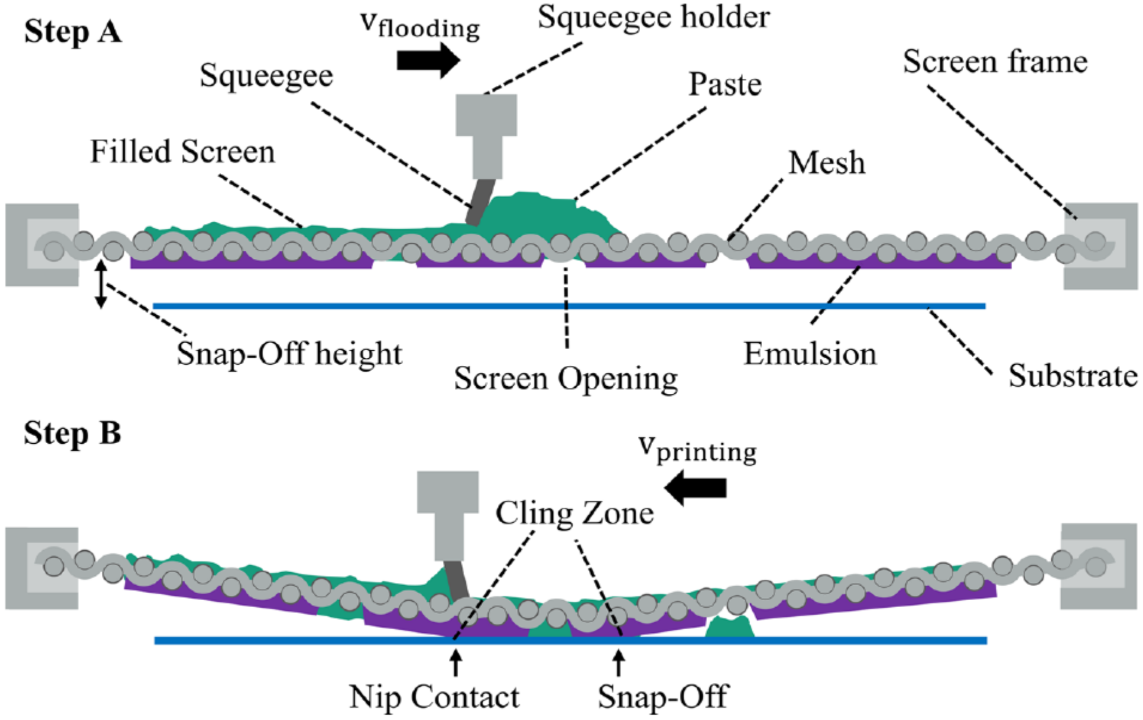
Screen-Printing metallization system

Screen-printing line

Loading station	Screen Printer	Drying furnace	Flipper	Screen Printer	Drying furnace	Annealing/ firing furnace	Unloading station



Printing mechanism [1,2]

- Step A :
  - Flood moves over the screen
  - Fills the mesh with paste.
- Step B:
  - Squeegee pushes the screen down to the substrate until contact.
  - Pressure induced snap-off behind the squeegee
  - Screen moves back to its initial position
  - Paste remains on the substrate at the defined location

[1] Tepner S, SOLAMT, 2019
[2] Tepner S, PIP, 2023

Screen-Printing metallization system

Screen-printing line

Design considerations for an industrial screen-print line

- Cycle time
- Throughput
- Yield loss and uptime
- Positioning and alignment accuracy
- Process control and monitoring (closed loop/open loop)
- Testing and sorting

- Metallization pattern (with or without busbars) – decide the number of screen print stations
- Screen-printing methodology (single/double/dual print) –
  - Low alignment tolerance (± 8-10µm)
  - Advanced optical and alignment systems

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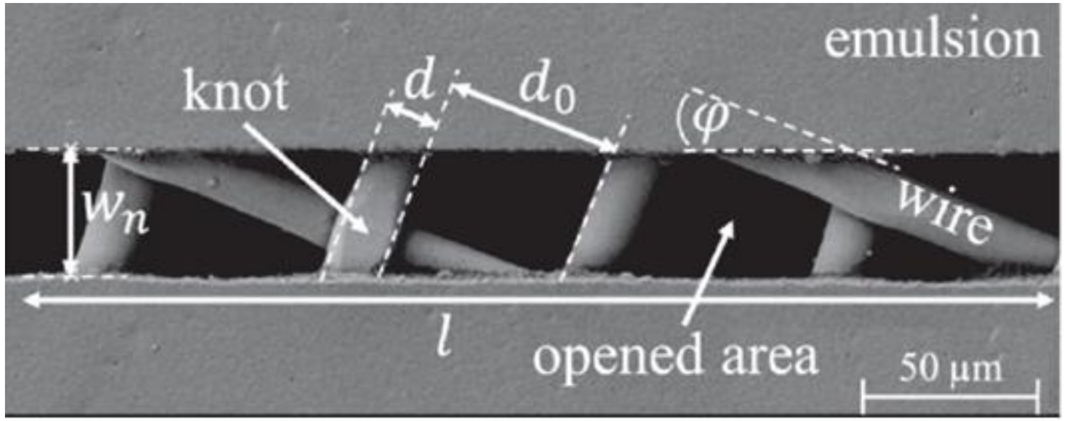
Screen-Printing metallization system

Screens

- Steel/tungsten wires woven and stretched over a metal frame
- Print areas defined by emulsion
- Mesh count – # of openings/inch, ranges from 250 – 480.
- Wire diameter: 10 - 25 µm
- Screen longevity ∝ wire diameter, wire material & mesh count



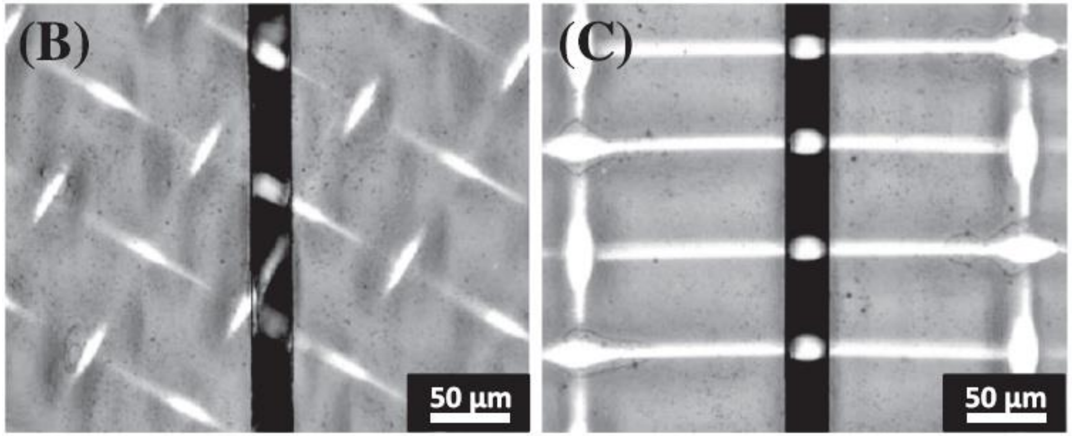
SEM image of a regular screen opening [1]

[1] Ney L, AIP Conf Proc., 2019

Screen-Printing metallization system

Screens

- 22.5° screen angle - established standard
- Recent shift towards 0° screen angle – knotless screen
- Knotless sceen: knots absent from the finger openings – suitable for fine-line printing.
- Precise alignment of finger opening required
- Higher paste transfer, shorter screen life



SEM image of a screeen with mesh angle B) 22.5° and C) 0° [1]

[1] Lorenz A, EUPVSEC, 2018

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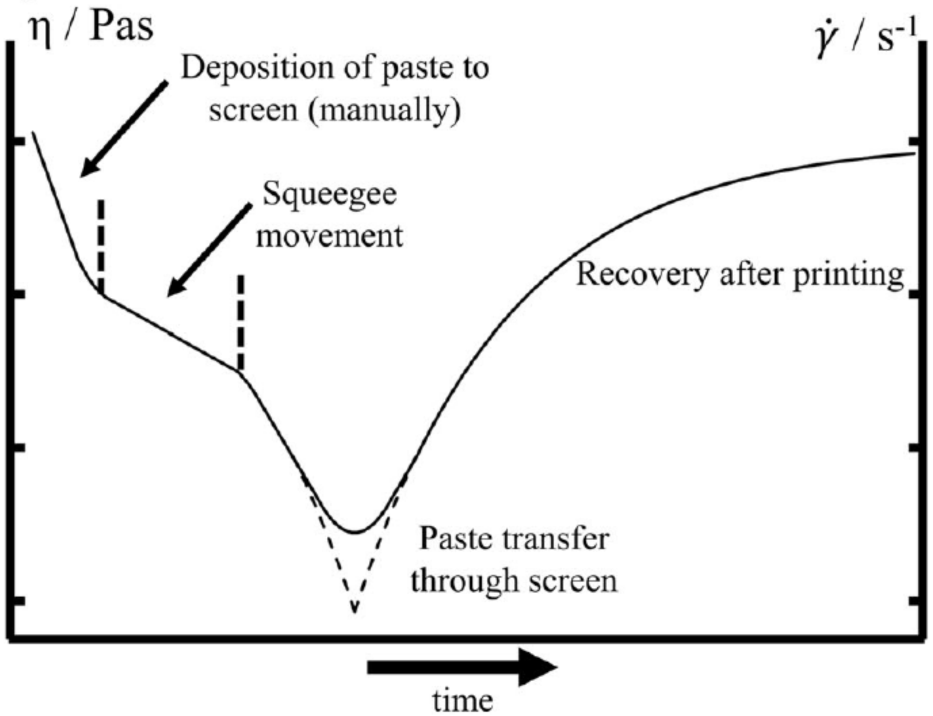
Screen-Printing metallization system

Pastes

- Pastes – crucial for solar cell performance
- Metal FT pastes – Metal particles (94-97%, 2-5 µm), glass frits, organic binders, solvents and rheological additives.
- Paste manufacturers usually provide screen details for a particular paste
- Pastes are tailor-made to suit a given production line's requirement
- Content and impact of paste constituents – proprietary information, competitive advantage



Schematic diagram for the viscosity and apparent shear rate during the different stages of the screen printing [1]

[1] Tepner S, PIP, 2023.

Screen-Printing metallization system

Pastes

- High-temp metal contact to n^+
  - Ag paste, Pb glass frits
  - Ag doped glass frits

- High-temp metal contact to p^+
  - Ag-Al paste, Pb glass frits
  - B doped glass frits
  - Al Pastes, with or w/o glass frits

- Low-temp metal contacts
  - Ag paste, no glass frits
  - Higher percentage of Ag than FT pastes

[1] Tepner S, PIP, 2023.

Screen-Printing metallization system

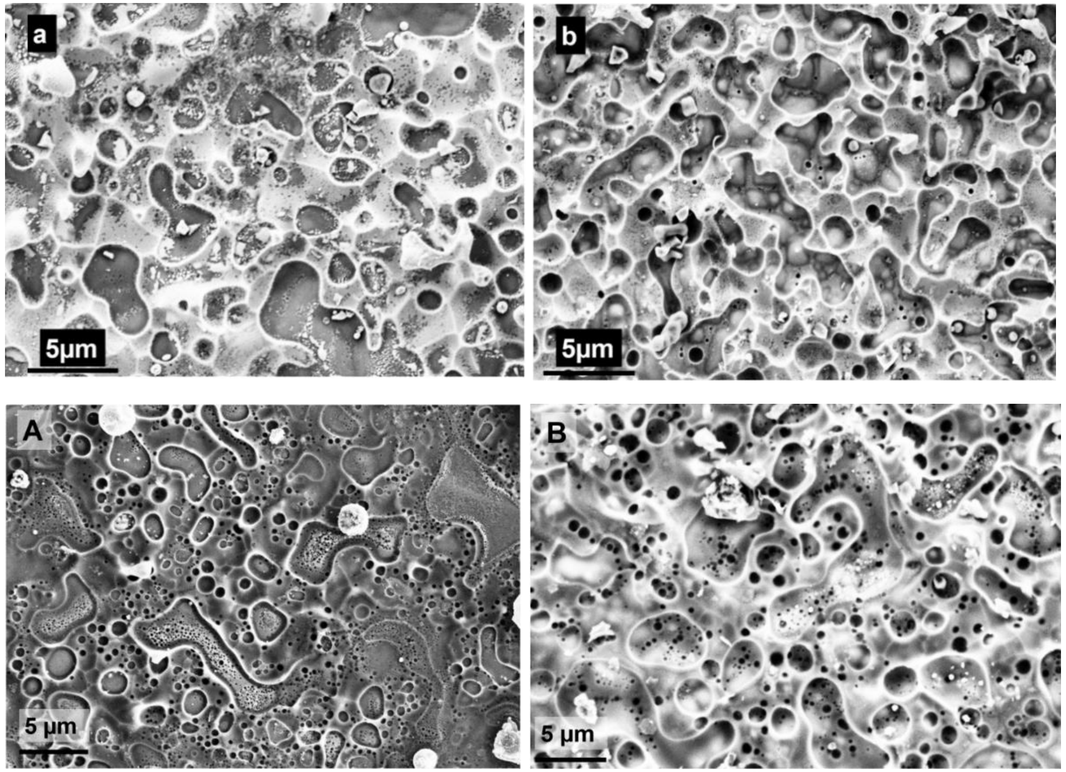
Pastes

- ❑ Surface morphology affects fingers morphology and contact properties
- ❑ Historically, FT Ag pastes developed for textured surfaces
- ❑ Recent focus on TOPCon – FT pastes for planar surfaces [1]
- ❑ Glass layer formation and dis-tribution – prime contributer [2]

Planar | Textured

N$^+$ poly-Si

P$^+$ poly-Si



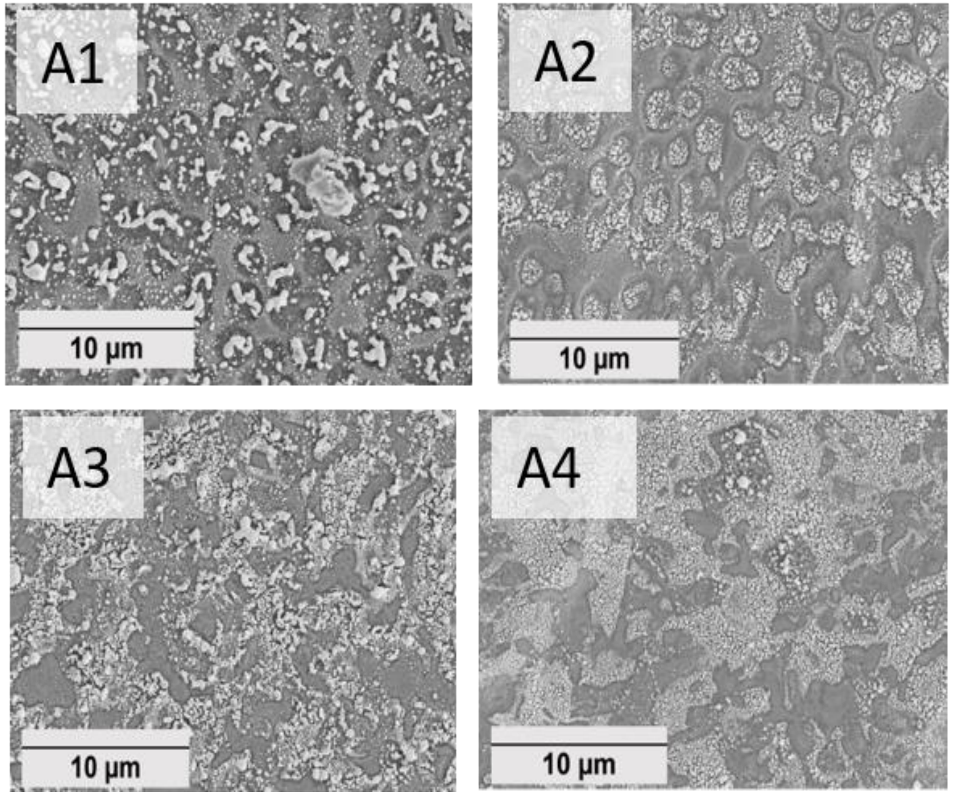
SEM images of the glass layer fomred with FT Ag paste and Ag-Al paste on n$^+$ and p$^+$ poly-Si, resp. [2]

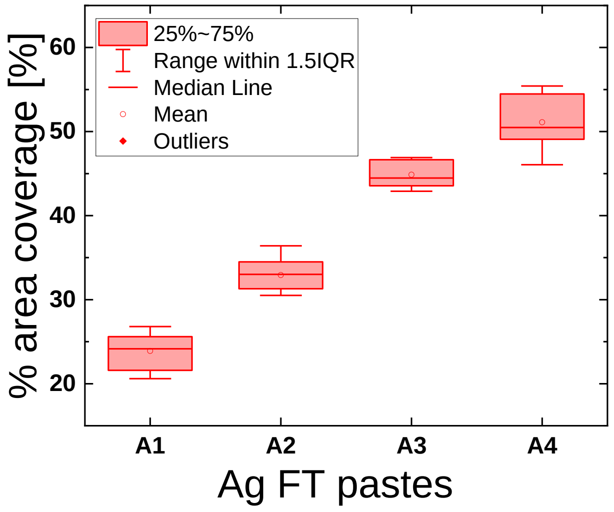
[1] Padhamnath Pradeep, SOLMAT, 2020
[2] Padhamnath Pradeep, PhD Thesis, NUS, 2021..

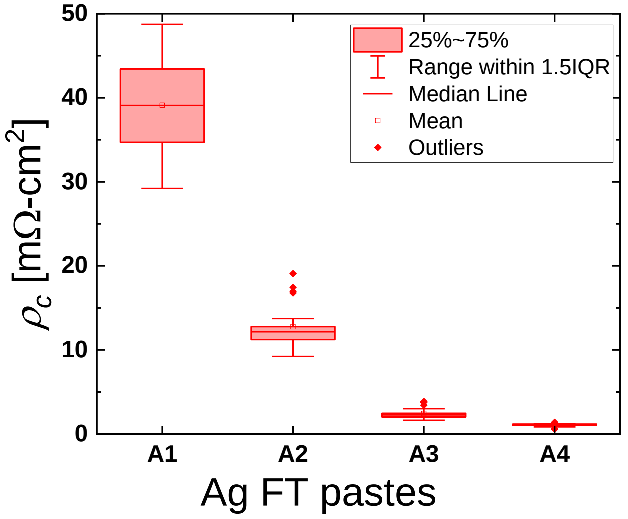
Screen-Printing metallization system

Pastes

- Ag FT pastes for n^+ poly-Si on planar surfaces







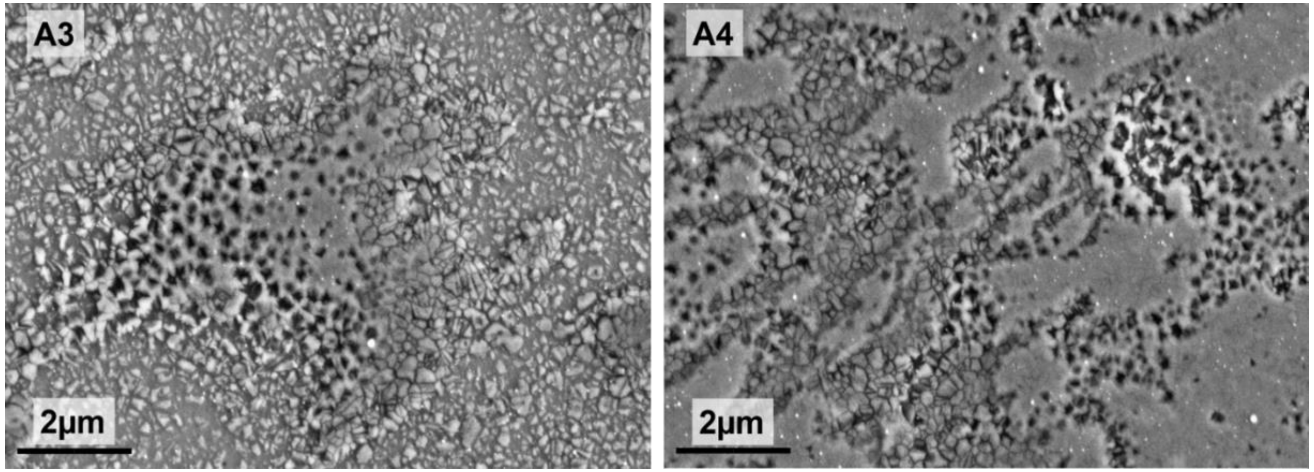
- Distribution and size of crystallites impact the contact resistivities [1,2]
- Finer particles, denser distribution preferred

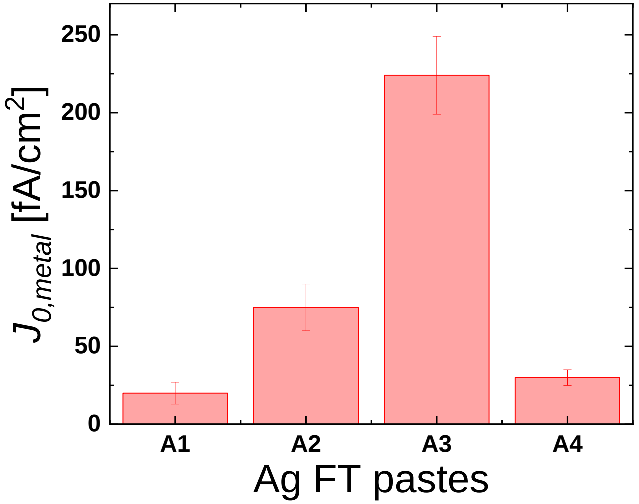
[1] Padhamnath Pradeep, SOLMAT, 2020
[2] Padhamnath Pradeep, PhD Thesis, NUS, 2021..

Screen-Printing metallization system

Pastes

- Ag FT pastes for n^+ poly-Si





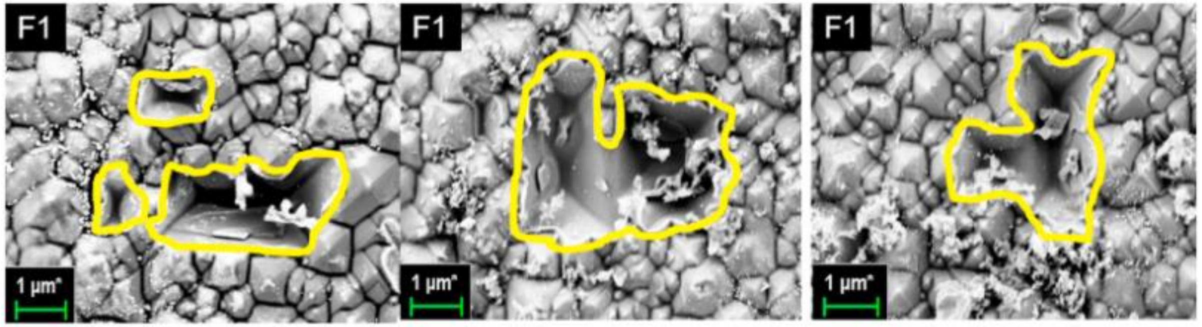
- Etching of the poly-Si layer by the glass particles crucial for passivated contacts

- Lesser the etching of the poly-Si & shallower the etch pits – the lower the $J_{0,metal}$ [1,2]

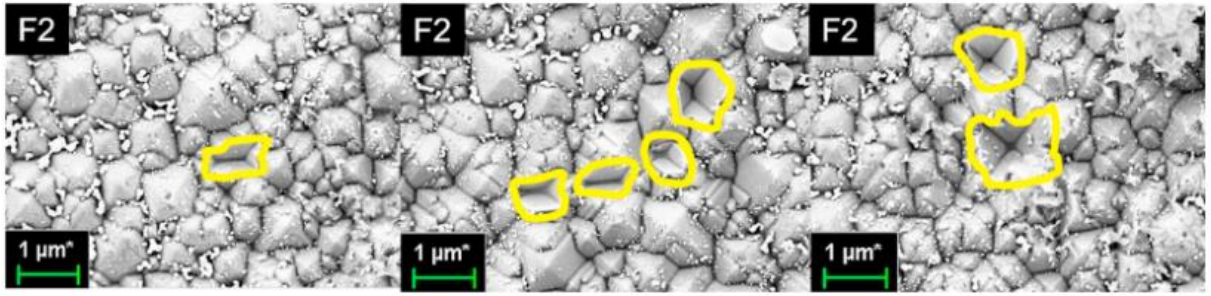
[1] Padhamnath Pradeep, SOLMAT, 2020
[2] Padhamnath Pradeep, PhD Thesis, NUS, 2021..

Screen-Printing metallization system

Pastes



- ❑ ρ_c = 1.1 mΩ-cm^2
- ❑ $J_{0,metal}$ = 1805 fA/cm^2



- ❑ ρ_c = 1.2 mΩ-cm^2
- ❑ $J_{0,metal}$ = 793 fA/cm^2

- ❑ Smaller etch pits by Ag-Al paste on p$^+$ c-Si → lower $J_{0,metal}$, higher V_{oc}

[1] Padhamnath Pradeep, SOLMAT, 2020.

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Challenges and opportunities

- ❑ Throughput – economic viability in face of increasing material costs

- ❑ Processing thin wafers with high mechanical yield

- ❑ Alignment accuracy ± 5 µm or better – Advanced processing
  - ➢ Dual Printing
  - ➢ Double Printing
  - ➢ ABC solar cells
  - ➢ Alignment between different equipment in production line (e.g. laser processing)

- ❑ Low-temperature metal paste/alternative /advanced pastes
  - ➢ Screen-paste-printer interaction
  - ➢ Paste – screen system iterative design
  - ➢ Non-metallic/polymer pastes

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Future outlook

Screens

- Advanced materials for wires and emulsion
- Increased longevity
- Improved material transfer from narrower openings
- Printing finer fingers (< 20 µm)
- Designing screens for advanced pastes beyond the regular viscosity ranges
- Advanced alignment features/fiducials

Future outlook

Screen-printer

- Patterning using screen-printing (eg:etch paste)

- Printing of thin films
  - Pvk-Si tandem solar cells
  - Absorber layers

- Advanced optical alignement systems
  - Higher resolution cameras
  - Advanced optical sources (IR, UV)
  - Closed loop alignment systems (< 1 s)
  - Multiple alignment inputs (edge, fiducials, patterns)

- Advanced capabilities aligning with industry 4.0
  - Automated screen cleaning
  - Automated screen replacement

Challenges, opportunities and future outlook

Future Outlook

- ❑ Paste

  - ➢ Developing Ag paste alternatives
    - Low-temperature Cu paste
    - High-temp FT copper paste
    - Coated particle pastes

  - ➢ Improving paste properties
    - Efficient material transfer through narrow openings
    - Lower spreading immediately after printing

  - ➢ Low-tempertaure pastes for Pvk based tandem solar cells
    - Alternatives to metal paste (polymer, carbon)
    - Low-tempertaure sintering (100-120°C)

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Summary

- Flat-bed screen printing of solar cell metallisation – industry leading for more than 5 decades

- Robust, efficient, lower cycle time and high throughput

- Cost-effective – lower maintenance and consumables cost

- Screen-printing technology
  - Mainstay of industrial production environment
  - Improvements in automation, lower maintenance - lower costs
  - Machine-screen-paste interactions – important design factor
  - Advanced alignment – required for several advanced printing strategies.
  - Advanced features, closed loop feedback relavant to industry 4.0

Summary

- Screen
  - Advanced wire material – improved strength and longevity
  - Thinner finger openings, improved material transfer (knotless screens)
  - Improved emulsion material, additives, coatings to improve paste transfer and finger profile retention

- Paste
  - Improved material transfer through thinner mesh openings
  - Low-temperature annealing for Pvk-Si tandem aplications
  - Alternatives to Ag paste – lower costs
  - Finer particle size, coated particles
  - Optimized glass frits for controlled etching and improved electrical properties
  - Thixotropic additivies for improved printing performance
  - Close collabortion with screen and solar cell manufacturers

Acknowledgment

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