Aerosol-Printed Silicon Solar Cell Exceeding 20% Efficiency

Crystal-Clear-Workshop

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Motivation, Screen print contact - “new”-contact

- Reduced contact area
  - reduced shading losses
  - reduced recombination
- Aspect ratio
  - higher conductivity
  - reduced series resistance
- Good electrical contacts on lowly doped emitters
  - improved blue response
  - reduced recombination
Content

- Seed layer concepts
- Aerosol print technique
- Ink preparation at Fraunhofer ISE
- Contact structure and formation
- Application: High efficiency solar cell
Two layer concept: Seed-layer and conductive-layer

Seed-layer
- Evaporation of contact metals through a mask
- Direct laser scribing
- Electroless plating of contact metals
- Fine line screen print
- Aerosol-jet print / Ink-jet print

Conductive-layer
- Plating (light induced or electroless)
- Multiple printing of highly conductive materials
Light-induced plating

- Backside connected via external power supply to Silver anode
- Illumination induces negative potential on front side
- Positively charged Ag⁺-ions are attracted by the illuminated front side and deposited along the seed layer
Light-induced-plating – industrial realization

- Inline LIP at Fraunhofer ISE
- Two machines are available, for Ag and Cu
Schematic of an aerosol printer
Aerosol print head

- d = 18 µm
- Ø = 100 µm (nozzle opening)

Diagram showing:
- Metal Aerosol
- Sheath gas
- Nozzle
- Aerosol Jet
- XY-Table
Printing systems
Simulation: optimized contact width

- Influence of optical losses
- Influence of electrical losses
- Dependent on contact resistivity

Mette A., *New Concepts for Front Side Metallization of Industrial Silicon Solar Cells*, Universität Freiburg
Functional ink materials

- Metal powder - Silver
  ⇒ Conductivity and contact

- Glass frit (Metal Oxides)
  ⇒ Contact formation and adhesion

- Organic vehicle system (Solvents, binder, dispersant agents, rheological additives…)
  ⇒ Adjusting the ink on the used printing system
    (Screen print, Aerosol print, Inkjet print…)
Ink - Preparation

Tools:

- Crushing
  → Mortar
  → Ball mill

- Mixing
  → Agitators
  → spatula and beaker

- Dispersing
  → Ultra sonic finger/bath
  → 3 mill chair

www.d-firma.de/bilder/mischen.jpg
Aerosol contact after printing

- Single printed, dense line
- Line width <40 µm using a 200 µm nozzle
- Line height about 1-2 µm
- Height:width < 1/20

![Graph showing contact height vs. contact width with a peak at approximately 38 µm.](image)
Aerosol contact after firing

- Evaporation of solvent and binder
- Sintering of silver particles
- Reduced line conductivity

⇒ Light induced plating
Aerosol contact after LIP

- Aspect ratio increases 1:4
- Improved conductivity
  \( \rho_f \approx 2 \times 10^{-8} \, \Omega m \)
- Higher reflection (optical width about 70\% of real contact width)
Reverse contact formation

plated silver  LIP-Silber

ISE_MAO 18.0mm x400 SE(U)

100um
Reverse contact formation

- LIP silver is removed by nitric acid
Reverse contact formation

- LIP silver is removed by nitric acid
- Printed silver is removed
Reverse contact formation

- LIP silver is removed by nitric acid
- Printed silver is removed
- HF dip to remove the glass layer
Reverse contact formation

- LIP silver is removed by nitric acid
- Printed silver is removed
- HF dip to remove the glass layer
- Nitric acid to remove the silver crystallites
Current model of the contact formation

- Glass melts at about 500°C and wets the interface ink-solar cell
- PbO, dissolved in the glass reacts with the SiNx-layer and opens the ARC
- Both, silver and oxidized silicon is dissolved in the glass melt at about 800°C
- Dissolved silver crystallizes in form of small silver-crystallites during cooling

Schubert, G., *Thick film metallisation of crystalline silicon solar cells* 2006, Universität Konstanz
Mögliche Mechanismen des Stromflusses ohne LIP

Mette A., *New Concepts for Front Side Metallization of Industrial Silicon Solar Cells*, Universität Freiburg
Solar cells on Fz-Wafers

- Two different inks
  - Diluted screen print paste (ink A)
  - Designed at ISE (ink B)

- On three different emitters
  - 50 Ω/sq.
  - 70 Ω/sq.
  - 110 Ω/sq.
Process flow

Front and rear passivated solar cell
Process flow
Process flow

Contact firing
Process flow

Evaporation of Al on the rear
Process flow

Laser fired contacts (LFC)
Process flow

Light induced plating (LIP)
Process flow

Forming gas annealing (FGA)
Cell structure

- LIP-Silver
- Aerosol-printed seed layer
- Antireflexion coating and emitter
- LFC point contacts
- Thermal oxide
- Evaporated aluminum
Current and voltage

![Graphs showing current and voltage for different inks and ink B.](image)
IQE of the best cells of each emitter

- Influence of the emitter sheet resistance is visible in the short wave length region
- Comparable quantum efficiencies for all cells in the long wave length region
- Good reflection, due to a passivated rear and a aluminum mirror
Fill-Factor and efficiency

![Box plots showing Fill-Factor (FF) and efficiency (η) vs. sheet resistance (Rsh) for different ink compositions and values.](image-url)
Efficiency over one wafer

*) independently confirmed by Callab ISE
Contact resistance vs. emitter sheet resistance

- Contact resistance increases with increasing emitter sheet resistance.

- The contact resistance $R_c \times W$ for ink B (designed at ISE) is below 0.5 $\Omega$cm for all emitter sheet resistances.

![Graph showing the relationship between $R_c \times W$ and $R_{sh}$](image-url)
SEM image of Ag-crystallites on a 110 Ω/sq. Emitter
Conclusion

- Fine line printing is possible
- Low ohmic contacts can be formed on lowly doped emitters using ISE ink
- Processed solar cells achieving 20% efficiency
Thank you for your attention

More information:
*M. Hörteis, S. W. Glunz PIP-850 (online available)*