PROJECT "INNOMET" - EVALUATION OF INNOVATIVE GLASS-BASED PRINTING FORMS FOR SOLAR CELL METALLIZATION

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ABSTRACT: Within this work, we discuss the evaluation of innovative glass-based stencils starting with in-depth computational fluid dynamics (CFD) simulation of different channel geometries using COMSOL Multiphysics©. Based on these simulations, a special hour-glass shaped channel geometry has been identified which theoretically enabled the direct printing of contacts with a triangular cross-section using stencil printing. With the expertise of the involved partners LPKF Laser & Electronics AG and Christian Koenen GmbH, several sets of LIDE-structured glass foil stencils have been fabricated and tested on a semi-automatic screen printer at Fraunhofer ISE. Within these tests, the prediction of stencil-printed triangular contacts could be impressively verified on Cz-Si PERC solar cells. Due to the optimal reflection properties of such a contact shape, this could enable effectively “transparent contacts” in the future and thus represents a long-lasting dream of all solar cell metallizing specialists. Furthermore, glass foil nozzle plates were manufactured for the parallel dispensing technique by LPKF Laser & Electronics AG to demonstrate the proof of concept for an alternative, cost-effective material including production costs for nozzle plates compared to the standard material. LIDE-structured glass foils showed promising results in the multi-nozzle dispensing process to be used in the future within further optimization in the manufacturing process.

Keywords: silicon heterojunction (SHJ), metallization, fine line printing, stencil printing, parallel dispensing

1 INTRODUCTION

Optimizing the fine line metallization of silicon solar cells is one of the key factors for further increase of the cell performance. Impressive results have been demonstrated in the field of fine line screen printing recently [1, 2]. Besides, the performance aspects on the solar cell (reduction of shading, lateral conductivity of the grid), further aspects like reduction of silver laydown, process and material costs and throughput must be considered for the metallization step. Within the joint project “Innomet”, a consortium of project partners including Fraunhofer ISE, LPKF Laser & Electronics AG and Christian Koenen GmbH has developed a highly innovative approach to fabricate very precise printing forms for solar cell fine line metallization based on thin glass foil structured with the so-called laser induced deep etching (LIDE) process [3]. This process enables the cost-effective and highly precise structuring of very fine openings in glasses with a thickness of up to 1000 µm. The LIDE process enables high precision and quality processing of glasses in a two-step process: In a first step, the glass (i.e. borosilicate glass) is modified and structured by a laser step. The modified areas are then etched with a high selectivity in a subsequent wet etch process (**Figure 1** and **Figure 2**).

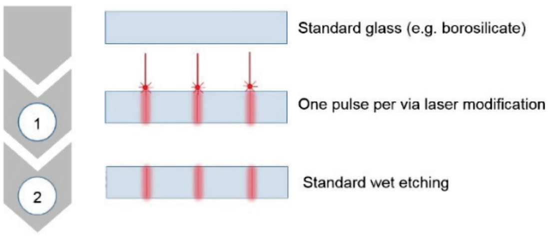

Figure 1: LIDE approach for the structuring of thin glass foils in a two-step process (image taken from [3] with courtesy of LPKF Laser & Electronics AG).

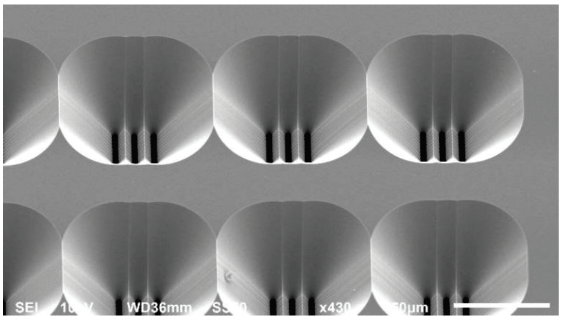

Figure 2: SEM images of LIDE-structured glass foil (image with courtesy of LPKF Laser & Electronics AG).

Within the project, two approaches are considered: On the one hand stencil printing [4] which has been applied for decades for printing of solder pads in the field of printed circuit board (PCB) production [5] as well as solar cell metallization [6, 7] using metal-foil stencils. On the other hand multi-nozzle parallel dispensing [8–11], a highly promising approach for the contactless application of homogeneous fine line contacts on silicon solar cells. The potential of parallel dispensing as a highly promising metallization technique for solar cell applications with strong benefits regarding throughput, silver reduction and effective silver usage has been demonstrated in multiple studies [12, 13]. Parallel dispensing has been successfully applied in silicon photovoltaics [14] as well as in thin-film photovoltaics [15].

Within this work, we evaluate the applicability of the LIDE technology to fabricate high-precision fine line stencils as well as nozzle plates for parallel dispensing based on thin glass foil. We show that the LIDE approach could enable a promising and cost-effective alternative to elaborately structured metal foils.

2 EXPERIMENTAL

2.1 Simulation of channel geometry

In order to evaluate the optimal channel geometry of glass-based stencils regarding paste flow and printing result, a comprehensive computational fluid dynamics (CFD) numerical simulation of different channel geometries using COMSOL Multiphysics© has been carried out which is described in detail in [16, 17]. Based on the results of various simulation runs, a special hour-glass shaped channel geometry (**Figure 3**) has been identified as a very promising channel design which theoretically enables printing of contacts with a triangular shape (cross-section).

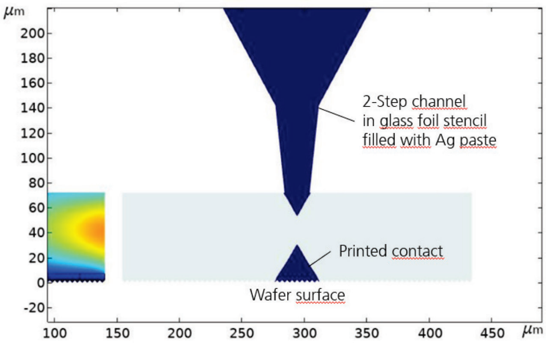

Figure 3: COMSOL Multiphysics© CFD simulation of channel geometry and stencil printing process with the result of triangular-shaped contacts [16, 17].

2.2 Fabrication and evaluation of glass foil stencils

With the expertise of the involved partners LPKF Laser & Electronics AG and Christian Koenen GmbH, several sets of glass foils with an initial thickness of $d_{glass} = 400$ µm are structured using the LIDE process. Based on the results of the previously conducted comprehensive CFD simulation, prototype glass stencils with a solar cell front side grid layout (busbarless layout, 100 fingers) using an optimal two-step channel geometry are realized. Microscopy measurements of the finger channels determine the width of the LIDE-structured channels with approx. 200 µm on the squeegee side and approx. 21 µm on the printing side of the stencil. The integration of structured glass foils into a stencil frame with an adequate stability for the printing process proved to be particularly challenging. This challenge could be solved by developing a new technique to mount the glass foil into the frame using the expertise of the project partner Christian Koenen GmbH. Using this method, stencils with a printing area of 300 mm x 300 mm are fabricated (**Figure 4**) for fine line printing tests using an EKRA XS-2 semi-automatic screen printing machine at Fraunhofer ISE and commercially available PERC silver (Ag) paste. In order to evaluate the optimal printing parameters, the printing test is carried out with varying printing speed ($v_{print} = 20$ mm/s to $v_{print} = 300$ mm/s) and printing pressure (p = 0 – 20 N).

Industrially pre-fabricated Cz-Si PERC solar cell precursors without metallization are used for the metallization process. The printing result and the three-dimensional geometry of the printing contacts is analyzed with confocal laser-scanning microscopy (CLSM) and subsequent image analysis using the Fraunhofer ISE tool "Dash" [1]. Furthermore, scanning electron microscopy (SEM) is applied to further analyse the finger geometry on selected contacts.

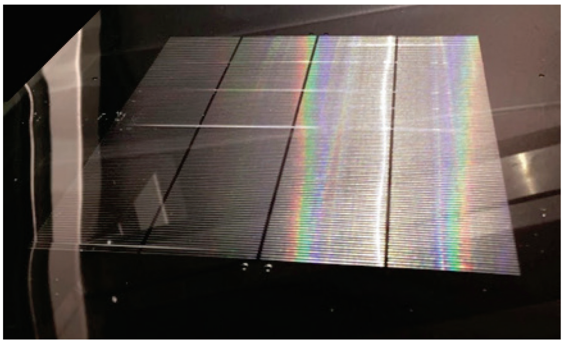

Figure 4: LIDE-structured glass foil stencil with busbarless fine line grid.

2.3 Fabrication of LIDE-structured glass foil nozzle plates and evaluation of parallel dispensing process

First pre-tests regarding the application of the LIDE-process for the fabrication of dispensing nozzle plates revealed several challenges:

- Reproducible geometry of the LIDE-structured nozzle openings within the nozzle plate
- Mounting of the nozzle plate on the dispensing head with sufficient sealing and mechanical stability
- Mechanical stability of the glass nozzle plate during the dispensing process
- Wetting behavior of the solvent on the bottom side of the nozzle plate

To evaluate and assess the optimal parameters of the glass material and the LIDE process for dispensing nozzle plates, 24 different variations of glass nozzle plates (each plate with 15 parallel nozzle openings) are fabricated by LPKF Laser & Electronics AG and analysed at Fraunhofer ISE. The following parameters have been varied:

- Initial thickness d of glass foil: $d_{glass} = 300$ µm and $d_{glass} = 400$ µm
- Nominal nozzle diameter D: D = 25 µm, D = 30 µm, D = 35 µm
- Nozzle shape (with/without trench)
- Coating: glass foil with and without Titan (Ti) coating (wetting behaviour)

A test series in five steps has been carried out for each glass nozzle plate design. In the first step, three individual nozzle plates of each variation were characterised by means of microscopy regarding the nozzle diameter in x- and y-directions of all nozzle openings. Based on the optical characterisation, the nozzle plate with the smallest deviation of the nozzle diameter over the 15 nozzles is selected and bonded to a nozzle plate carrier. This bonded nozzle plate was mounted to the R&D print head 'GECKO' [18] and is used for stability analysis using a commercially available low-temperature silver paste. The stability tests are carried out on a specific test setup using the R&D print head in combination with a rotating roll.

Within the stability analysis, it is investigated whether homogeneous, straight paste threads can be extruded from the nozzle openings and whether the glass nozzle plate is mechanically stable when applying the process pressure load. Subsequently, the glass nozzle plate is cleaned to visually characterise the nozzle plate regarding hairline cracks in the glass substrate and changes of the nozzle openings. If the glass nozzle plate shows no damage, dispensing tests are carried out on Cz-Si wafers with a size of 156.75 mm x 156.75 mm. The process velocity is varied between $v_{process}$ = 50 mm/s and $v_{process}$ = 500 mm/s to evaluate the optimal dispensing conditions for a homogeneous result on the whole wafer area. Finally, the printed contacts are characterised regarding finger height and width using a 3D confocal laser scanning microscope.

3 RESULTS AND DISCUSSION

3.1 Glass foil stencil printing

Glass foil stencils with an initial thickness of d_{glass} = 400 µm proved to be stable during the process and showed no traces of mechanical damage or micro-cracks after the process. The best printing result is achieved at a printing velocity of v_{print} = 150mm/s. At velocities below and above 150mm/s, the paste transfer was insufficient, resulting in very inhomogeneous contact fingers with many interruptions. CLSM analysis of selected homogeneous contact fingers results in a mean core finger width of w_f = 29 µm and a mean finger height of h_f = 24 µm. Due to remaining local deviations along the LIDE-structured fine line grid, it was not possible to print a completely homogeneous metallization grid with sufficient quality for solar cell metallization onto the Cz-Si precursors. Ongoing effort is done by LPKF to improve the homogeneity of the glass channels.

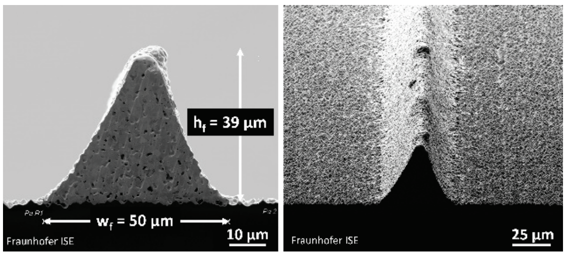

Figure 5: SEM images of contacts with triangular shape printed with LIDE-structured glass foil stencils.

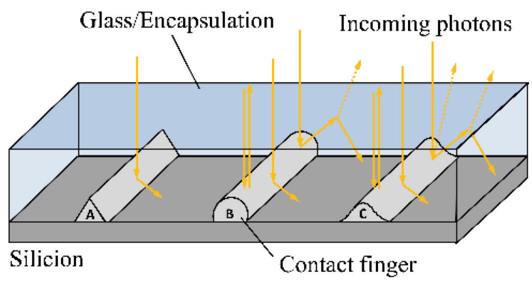

Figure 6: Schematic of internal reflection properties of solar cell contacts within the module. Triangular-shaped contacts are particularly beneficial due to internal back-reflection. Modified image based on [19, 20].

However, a particularly remarkable result could be achieved by printing contacts with almost perfectly shaped triangular cross-section which impressively confirms the prediction of the previously conducted CFD simulation [17]. SEM images of selected contacts confirm the triangular cross-section of the contacts (**Figure 5**). Fingers with a triangular shape are expected to have particular advantageous reflection properties within the module due to an effective internal reflection of incoming light into the solar cell [20] (**Figure 6**). In an optimal case, such fingers can even be considered as “effectively transparent” [21, 22]. Further improvement of the LIDE-structured glass foil stencils could enable a direct printing process of triangular fingers over the whole metallization grid.

3.2 Glass foil dispensing process

The microscopic analysis of the LIDE-structured nozzle plates revealed a sufficient, yet still expandable quality of the nozzle openings. The maximum deviation between 15 nozzle openings within one glass nozzle plate is up to 2 µm. The average diameter of nozzle openings is determined with $D_{n,25}$ = 24.8 µm ± 0.6 µm for the 25 µm-nozzles and $D_{n,35}$ = 36.7 µm ± 2.6 µm for the 35 µm nozzle plate. Simulation results by Pospischil et al. show that already a small variation in nozzle diameter leads to an inhomogeneous flow profile and consequently to an inhomogeneous mass flow and thus to an irregular printing image and local disruptions within the dispensing process [23]. Thus, further improvement will focus on reducing the deviation between the nozzle openings to a value < 1 µm.

Within the stability tests, the glass foil nozzle plates showed a comparable mechanical stability to the reference nozzle plates. The nozzle plate configuration with an initial glass thickness of d_{glass} = 300 µm, Titan coating and a nozzle opening of d_{nozzle} = 30 µm obtained the most promising results during the stability plate and thus is selected for a metallization test run on Cz-Si wafer material. Using this configuration, a full-area solar cell wafer (156.75 mm x 156.75 mm) is successfully metallized with a busbarless grid of 150 dispensed fine line contacts using low-temperature silver paste for silicon heterojunction solar cells at a dispensing velocity of $v_{process}$ = 240 mm/s (**Figure 7**).

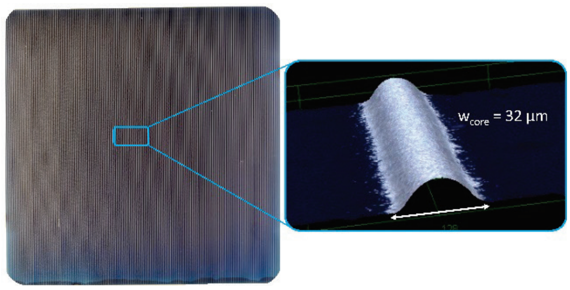

Figure 7: Dispensed full-area solar cell and CLSM image of a dispensed contact using glass foil dispensing process.

Subsequent CLSM analysis of the finger geometry revealed a mean core finger width of $w_{f,c}$ = 32 µm. Similar results are achieved with the reference dispensing process at the time of the experiment (2021). A wet paste laydown of m_{Ag} = 0.44 mg per contact finger is determined on R&D level using glass foil nozzle plates. Comparing these results to the reference dispensing process using standard metal nozzle plates, the results are encouraging. Yet, further optimization of the process will be necessary to obtain comparable results. Recently, a wet paste laydown of m_{Ag} = 0.30 mg per contact finger for low-temperature curing Ag pastes has been demonstrated by HighLine Technology GmbH on industrial level [10]. In 2022, the paste laydown could be even reduced to m_{Ag} = 0.27 mg per contact finger on R&D level for the dispensing process by using standard nozzle plates [13].

To obtain similar results, further R&D activities by LPKF will focus on improving the LIDE-process with respect to a reduced deviation of the nozzle openings. It is expected that comparable results to the reference can be achieved using optimized glass foil nozzle plates.

4 CONCLUSION AND OUTLOOK

In summary, the adressed solutions and results of the project "Innomet" provide two highly promising approaches for the next-generation fine line metallization of high-performance solar cells. Stencil printing based on LIDE-structured glass foils with funnel-shaped channel geometry offers the very promising opportunity to realize contacts with triangular-shaped cross-section. This offers the very interesting potential to realize effectively transparent contacts on silicon solar cells using a reliable stencil printing process. While the proof of principle has been successfully demonstrated within the project, further effort is required to enable an easy-to-handle and stable manufacturing procedure for glass foil stencil.

In the field of parallel dispensing, a successful proof of principle has been conducted regarding the fabrication and application of LIDE-structured nozzle plates for parallel dispensing of Si solar cells. Glass-based nozzle plates can be a promising approach to reduce costs and complexity of the nozzle plate manufacturing process. The feasibility of this approach has been successfully demonstrated with promising results regarding finger width and uniformity as well as process stability. Current R&D effort is focussed on improving the process reliability to reduce deviations of the nozzle opening size.

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