Front-side metallization by parallel dispensing technology

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ABSTRACT

Parallel dispensing technology as an alternative front-side metallization process for silicon solar cells offers the possibility of increasing cell conversion efficiency by 2% rel. by the use of commercial silver pastes designed for screen-printing technology. This efficiency gain is achieved through a significantly reduced finger width, and hence reduced shading losses, in combination with substantially improved finger homogeneities and high aspect ratios that guarantee sufficient grid conductivity at reduced paste lay-down. In this paper Fraunhofer ISE's development of a parallel dispensing unit that is integrated into an industrial, inline-feasible platform made by ASYS is discussed. A possible industrial application of the dispensing technology is supported by latest results from pilot processing as well as by basic economic considerations.

Introduction

Silicon solar cell metallization is still dominated by screen-printing technology, which offers a robust contact formation and proven long-term stability. Due to pressure from a rapid decline in retail module prices, however, it became necessary to significantly reduce Ag-paste consumption [1]. Consequently, paste and process development was motivated to achieve printed line widths of less than 50µm, but known issues – such as mesh marks, line spreading or screen wear – have not yet been overcome. Various thick-film technologies – for example stencil printing [2], pattern transfer printing [3] and co-extrusion [4,5] – are promising and have already reached significantly high technology-readiness levels. Nevertheless, some remaining challenges – including fragile and expensive stencils, additional consumable costs, and the competition of the fast-emerging screen-printing technology – have so far prevented a market breakthrough.

Dispensing technology, as described by Specht et al. [6] and illustrated in Fig. 1, offers a contactless, single-step metallization process that significantly reduces finger width and thus shading losses. Furthermore, a substantially improved homogeneity of dispensed fingers compared with screen-printed front-side contacts results in more-efficient metal paste usage [7]. In 2011 record cell efficiencies of 20.6% for 125mm × 125mm FZ p-type material using dispensing technology on metal wrap-through passivated emitter and rear cell (MWT-PERC) devices were presented by Lohmüller et al. [8]. Within the GECKO public research project, dispensing technology has been developed, in collaboration with industry partners ASYS, Heraeus and Merck, with a goal of industrial application.

> "Dispensing technology offers a contactless, single-step metallization process that significantly reduces finger width and thus shading losses."

Print head development

In order to compete with industrially established metallization processes, standard throughput rates needed to be achieved (i.e. 1,600 wafers/hour per printing tool [9]). One possibility for increasing the throughput is by parallel dispensing multiple fingers. Various approaches concerning this topic have been reported in the past [10,11].

Chen et al. [12] introduced a parallel dispensing unit incorporating several nScrypt SmartPumps [13] in parallel, each individually feeding two or three nozzles. With this approach, contact lines of only 47µm in width and a height of 34µm were reached at traverse speeds of up to 500mm·s^{-1} [14]. However, the number of contact

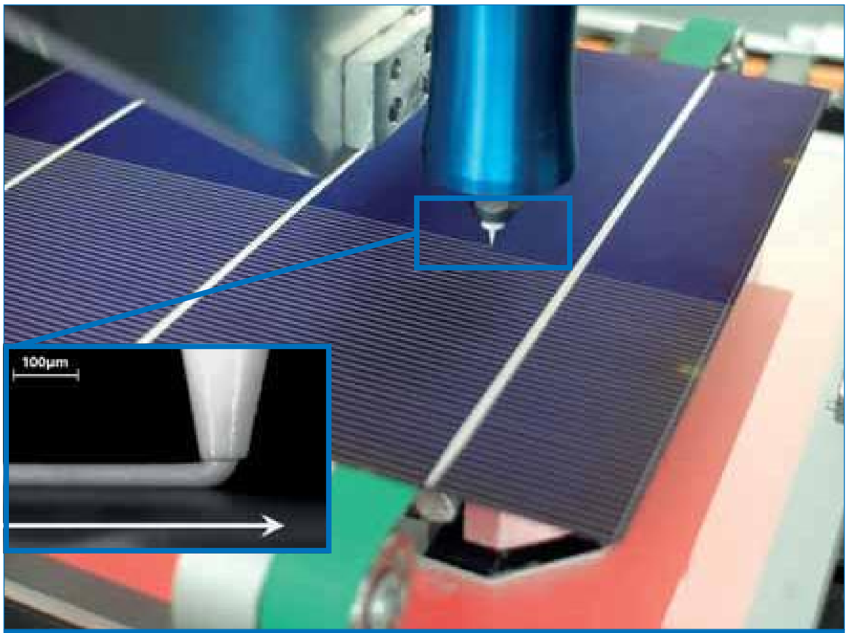

Figure 1. Single nozzle dispenser as used for initial process investigations.

fingers necessary on the front side increases with decreasing line width, since sufficient grid conductivity has to be provided. To allow the highest throughput rates, one nozzle per contact finger had to be possible, and the finger pitch needed to remain variable with only minor adaptation of the system. A modular set-up was therefore chosen, comprising a central paste supply unit and an exchangeable part containing ten nozzles with an opening diameter of 40µm and an initial pitch of 1.56mm, as necessary for a 100-finger grid.

At first, the central supply unit was developed by setting up a computational fluid dynamics (CFD) simulation of the system [15] that allows the description of paste flow inside any geometry in steady-state operation. Because of their high solid content, silver pastes support the formation of slip layers on solid walls and shear bands, as well as regions of plug flow, where the local shear stress does not surpass the yield stress and the paste remains in a solid state. Hence, a detailed rheological investigation of the metal pastes involved had to be conducted before setting up the CFD model. The central supply unit was then optimized until a homogeneous paste distribution to all nozzles could be ensured, despite the previously discussed issues concerning the yield stress metal paste.

The influence of fabrication tolerances (Fig. 2) on the dispensing process was isolated by sequentially changing the nozzle diameter of, for example, only one nozzle, thereby gaining an indication of the robustness of the solution [15]. The result was a ten-nozzle print head (Fig. 3), which had so far been applied to multiple cell

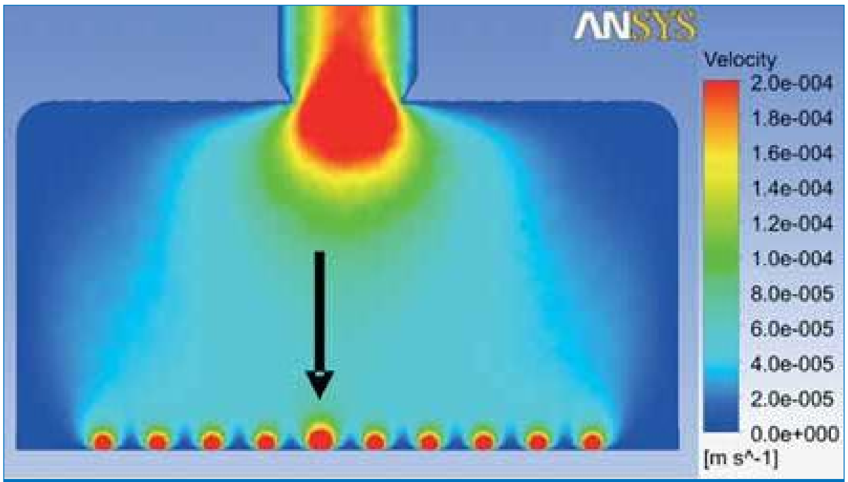

Figure 2. Velocity distribution of central paste supply unit over ten nozzles. Nozzle five was enlarged to simulate fabrication tolerances [15].

Figure 3. Ten-nozzle print head during solar cell metallization. With this system, process speeds above 600mm·s^{-1} can be realized.

Figure 4. Novel inline-applicable dispensing platform developed by ASYS, to be equipped with multi-nozzle print heads and auxiliaries.

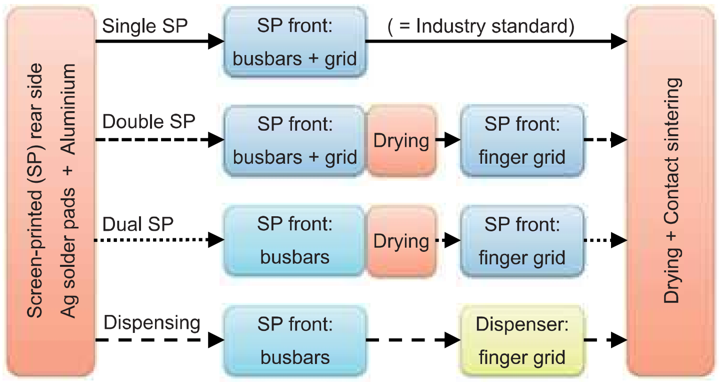

Figure 5. Possible integration of the dispensing platform into an existing back-end production line. Compared with screen- or stencil-based printing process, dispensing provides a simple drop-in replacement, since it does not require an additional post-print inspection or drying step [7].

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processing in recent years [7,16,17]. Industrial feasibility further required the development of an enlarged version of the print head, which covers the whole width of an industrial silicon wafer in order to dispense one cell within the required cycle time of a maximum of two seconds. This brand-new version has now been launched and will be presented at the 31st EU PVSEC in Hamburg [18].

Solar cell production process using dispensing technology

Besides the enhancement of parallel print heads at Fraunhofer ISE, ASYS developed an inline-applicable dispensing platform that has the same footprint as an ordinary screen-printing unit [7] (see Fig. 4). Equipped with the latest wafer alignment system that is also used in screen printers to ensure precise overlay alignment, this platform contains (among various other features) all the necessary interfaces to allow it to be directly integrated into a conventional solar cell production line.

Compared with other known enhancements of back-end metallization lines, the investment required for an inline integration will be low, since the dispensing unit can directly replace the post-print inspection unit in a conventional single-screen-printing line. The existing screen printer is then used for the application of the busbars following the dual-printing approach [19]. This allows a reduction in silver consumption and damage to the passivation layer underneath the busbars.

A second dryer between the two printing steps, as required for conventional dual or double (i.e. print on print) printing approaches, is not necessary (Fig. 5), since dispensing allows a contactless application of silver pastes, which can be deposited on already printed, wet busbars.

Rheological paste characterization

As mentioned earlier, a detailed rheological investigation was required beforehand in order to set up the CFD model during print head development. Because of the non-contact printing process, dispensing further offers the possibility of varying paste rheology over a much wider range than in the case of other thick-film printing technologies. The shape of the resulting contact fingers on the wafer can therefore be adjusted with respect to an optimum trade-off between cross-section area, shading and electrical contacting behaviour [20]. The main reason for this is that highly filled, thixotropic and shear-thinning silver pastes quickly regain their internal structure and return to a solid-like state after being exposed to high shear at the nozzle outlet. This already leads to higher aspect ratios than with conventional screen-printing, independent of the

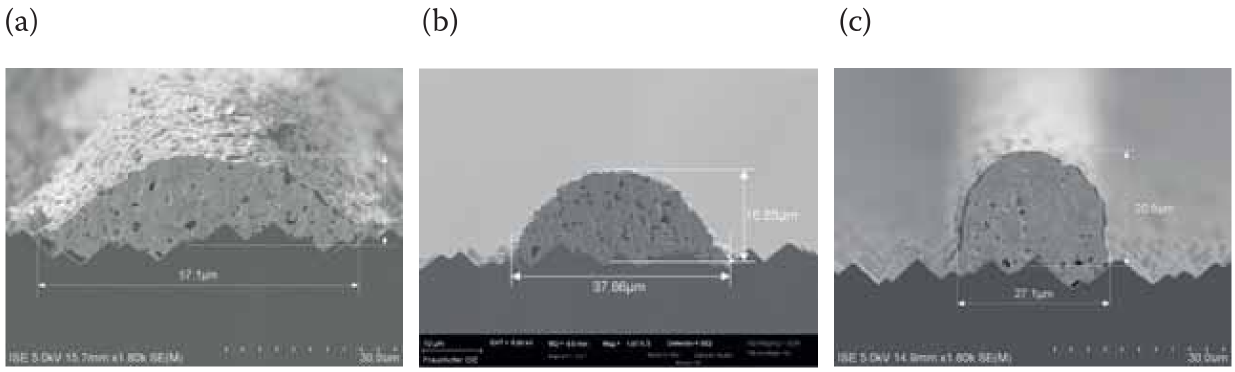


Figure 6. SEM images of printed and dispensed finger cross sections: (a) single-screen-printed reference; (b) dispensed sample when a screen-printing paste is used [7]; (c) dispensed sample when a rheologically adapted printing paste is used in order to increase yield stress and finger aspect ratio [16].

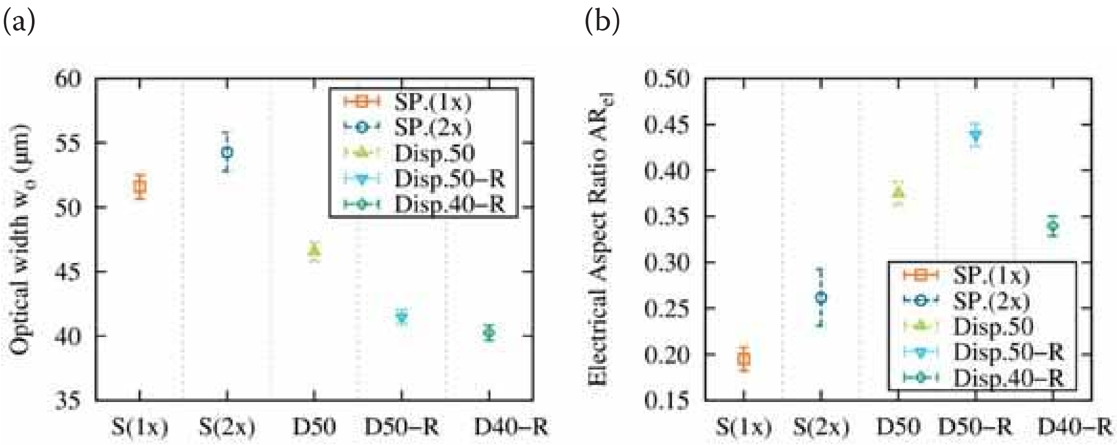
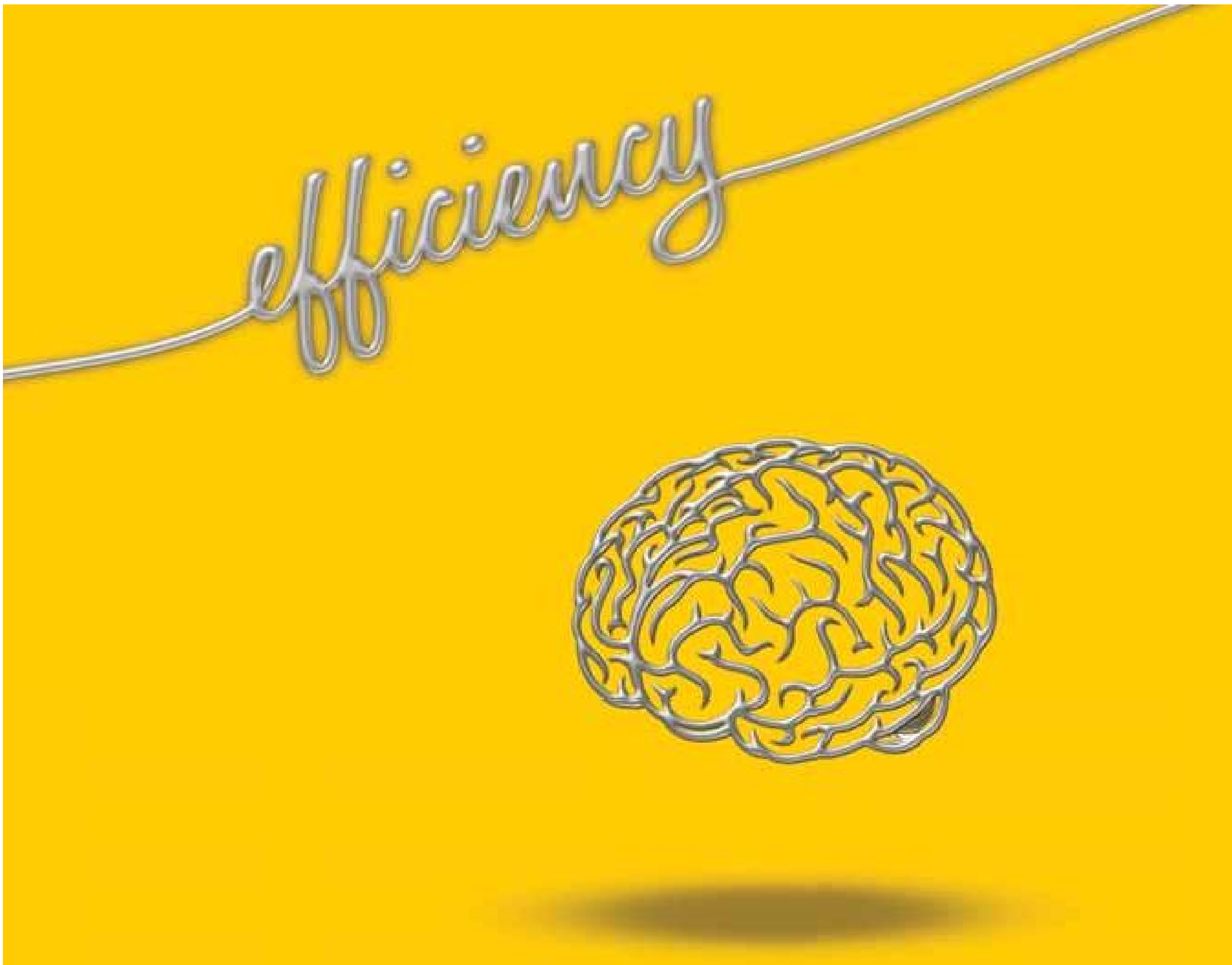


Figure 7. Resulting contact finger geometries for industrial Cz 156mm × 156mm material: (a) the optical finger width, which comprises the complete metal covered contact width of the finger; (b) the electrical aspect ratio, which describes the ratio between average finger height and optical finger width.

Heraeus



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applied paste, as indicated in Fig. 6. The characteristic shape of fine-line-dispensed contact fingers then changes drastically with increasing yield stress τ_y towards higher aspect ratios. A more detailed rheological description of this phenomenon has already been given in the literature [16,20].

> "Dispensing also offers the possibility of varying paste rheology over a much wider range than in the case of other thick-film printing technologies."

Analysis of contact finger geometries

Throughout the whole process development, printed and dispensed contact geometries were measured using an Olympus LEXT4000 laser confocal microscope; this allowed an in situ determination of confocal and height information within a finger section of approximately 256µm in length. An analysis of these geometrical data was performed using the Matlab-based software developed in-house, as mentioned in Pospischil et al. [17]. In the latest experiment, single SP(1×) and double SP(2×) screen-printed contact grids with screen openings of just 45µm and 40µm, respectively, were used as references. The dispensing group was divided into one with a nozzle opening of 50µm (D50), using exactly the same metal paste as the reference groups, and two that used a rheologically adapted paste with 50µm and 40µm nozzle opening diameters, i.e. D50-R and D40-R. Fig. 7 shows the plots of the resulting contact widths and the electrical aspect ratios for each of the five groups.

All dispensed samples exhibit a significantly reduced finger width and an increased aspect ratio. A comparison of the D50 and D50-R groups reveals that the rheologically adapted paste (-R) leads to a significant increase in aspect ratio, and thus to a further decrease in finger width, when the same nozzle diameter is used. Furthermore, as demonstrated by applying spectrally resolved light-induced current measurements (SR-LBIC), an increase in aspect ratio also improves internal reflective effects, thus allowing even smaller effective widths [7] and hence yielding further reductions in shading losses.

Interestingly, the aspect ratio for the last group, D40-R, is again lower than that for the D50-R group; this can be explained by the higher shear load inside the nozzle due to the smaller diameter in the former groups. Consequently, the finger width of the corresponding solar cells is still larger than 35µm, although a record finger width of 27µm has already been demonstrated with the same nozzle configuration but with a rheologically adapted paste of the previous generation [16] having an even higher yield stress.

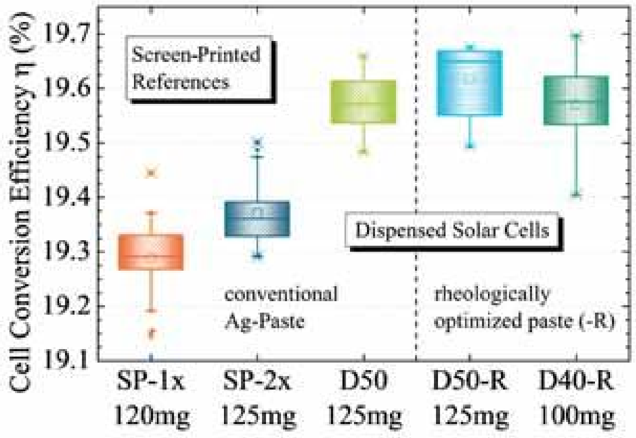


Figure 8. *I–V* results and wet paste lay-down for three different dispensing groups in comparison to single- and double-screen-printed reference cells. All dispensed groups show significantly increased cell efficiencies compared with both reference groups. The application of a nozzle diameter of only 40µm (last group) allows a substantial reduction in wet paste consumption compared with single-screen-printed samples. The application of a rheologically optimized printing paste should be considered in order to gain maximum cell efficiencies. A total of 270 cells on industrial preprocessed 156mm × 156mm Cz Al-BSF material were used in the experiment.

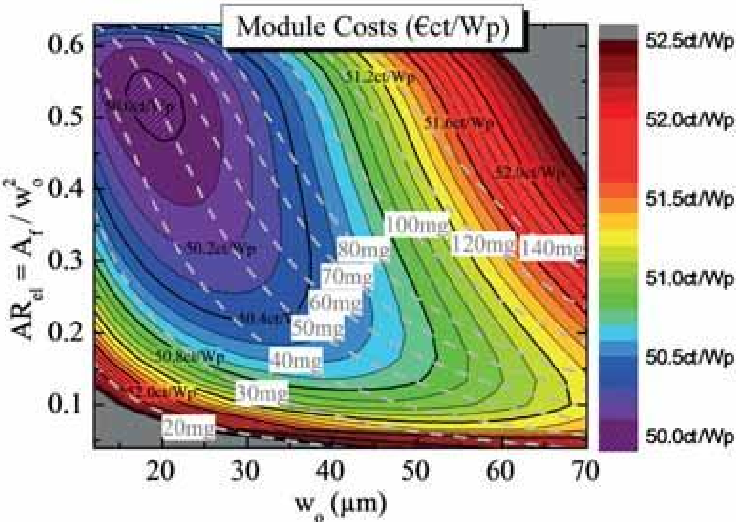


Figure 9. Simulation of estimated module costs as a function of finger width and electrical aspect ratio. Similar amounts of wet paste consumption are indicated by dotted lines. The data imply a homogeneous contact finger shape for any contact geometry. Each data point refers to the ideal number of contact fingers per cell from a cost perspective. For the simulation, a Cz p-type silicon wafer material, with industrial emitters of R_{sh}~90Ω/sq. and three dual-printed busbars (w_{BB} = 1.2mm), was assumed. (Data on cell manufacturing costs taken from Nov. 2014.)

Latest solar cell results for standard Al-BSF solar cells

Latest developments now permit the application of printing pastes designed for screen printing to the parallel dispensing prototypes. This improvement ensures the required contacting behaviour of the dispensed grids in combination with the previously discussed geometrically advantages of these ultrafine contact fingers that are applied at production speeds above 600mm·s^{-1}.

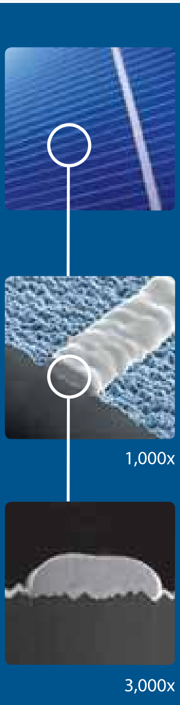
In the latest batch of industrial Cz Al-BSF solar cells, all the dispensing groups showed significant increases in efficiency of up to +0.4% abs. compared with the screen-printed references (see Fig. 8). Top values of 19.7% demonstrated the potential of the technology as an alternative metallization concept. This efficiency gain is mostly due to the significantly smaller finger width and thus higher values in J_{sc} and V_{oc}. For the first time, fill factors above 80% were demonstrated for all groups, the highest values being achieved for samples dispensed with a 50µm nozzle opening.

A detailed analysis of the series resistance revealed that all groups showed similar contact behaviour. The differences in R_s could therefore be directly attributed to differences in the finger grid resistance R_f. In this case, the dispensed groups using a nozzle opening of 50µm feature a value of R_f which has decreased by up to 28% compared with the value for the double-printed reference (SP-2×), which has the same wet paste consumption, but suffers from geometric inhomogeneities, such as mesh marks and paste spreading. Consequently, substantially improved homogeneity of dispensed contact fingers leads to more efficient usage of the applied silver paste and thus significant material savings. The total wet paste consumption, including contact fingers and busbars, for solar cells dispensed with 40µm nozzles was reduced by approximately 15–20% compared with that for both of the screen-printed reference groups, whether single or double printed. At the same time, efficiency increases of 0.3% abs. for the 40µm group were recorded.

Economic considerations

In order to optimize paste rheology and dispensing set-up in respect of cell efficiency and production cost, the Gridmaster analytic tool [21] was enhanced to handle extensive parameter studies by means of efficient, nested interval algorithms [17]. Here, the optimum number of necessary contact fingers is calculated on the basis of a combination of two independent input parameters, which are preferably chosen to be finger width (w_o) and aspect ratio (AR_{el}) for comparing screen-printed and dispensed contact grids.

An actual calculation is given in Fig. 9, which shows the expected module production costs as a function of the aforementioned input parameters; lines of equal wet paste lay-down are also indicated. If the geometrical results of Fig. 7 are taken into consideration, a cost-saving potential of approximately €ct1/Wp compared with single screen printing becomes apparent when dispensing technology is used, because of its high aspect ratio. Note that, in this case, differences between the technologies regarding the relative effective finger width and geometrical inhomogeneities, as well as additional influences, such as consumable and investment costs, yield losses and device throughput rates, have not been considered at this stage.



Conclusions and outlook

Fast-emerging thick-film printing technologies remain a dynamic challenge for any kind of alternative metallization technology. The possibility of directly applying screen-printing pastes, however, allows the enhancement of dispensing technology with regard to industrial cell processing. State-of-the-art contacting behaviour was therefore demonstrated on parallel dispensed solar cells, since the same screen-printing paste was printed and dispensed.

Dispensed grid lines offer a substantially more homogeneous contact shape and require 15–20% less silver than screen-printed fingers to obtain similar grid resistances. In the case of a rheological adaptation of the incorporated dispensing paste in order to achieve high aspect ratios, there is the additional benefit of smaller finger widths and reduced shading losses, as well as additional light reflected from the grid geometry at the module level. This fact, in combination with a substantially improved finger homogeneity, allows greater cell currents and fill factors, and at the same time a reduced silver paste consumption, compared with screen-printed reference solar cells. Parallel dispensing at production speeds above $600\text{mm}\cdot\text{s}^{-1}$ on an industrially feasible platform means that the introduction of the process to industrial back-end lines would allow a further increase in cell efficiencies at lower production costs in the mid term.

> “Dispensed grid lines offer a substantially more homogeneous contact shape and require 15–20% less silver than screen-printed fingers to obtain similar grid resistances.”

Once the 6″ dispensing print head has been launched, the focus will be on the biggest challenge – the development of a dispensing process that operates intermittently. This will include the optimization of all the components involved, especially the valve systems, in order to meet the requirements of this highly dynamic system.

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Maximilian Pospischil studied mechanical engineering at the Technical University of Munich and at Delft, and received his diploma degree from the former in 2009. In 2010 he joined Fraunhofer ISE as a Ph.D. student, and is currently a project leader within the printing technology group. His Ph.D. thesis topic concerns the development of an industrial front-side metallization process for silicon solar cells, based on dispensing technology.

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Raphael Efinger studied printing technology at the University of Printing and Media in Stuttgart and graduated in 2008. From 2009 to 2011 he worked at Day4 Energy Inc. as a research scientist in the field of cell-to-module integration using the multi-wire busbar approach. He has been working as a research engineer at Fraunhofer ISE since 2012.

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