IMPROVEMENT OF THE SOLAR CELL EFFICIENCY BY REDUCING THE SERIES RESISTANCE USING A PRINT-ON-PRINT-PROCESS

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ABSTRACT: The optimization of the front side metallization is one of the main efforts in solar cell business to improve the solar cell efficiency as well as to reduce the production costs. Fine line and high aspect ratio grid fingers are preferred to reduce shadowing as well as the series resistance. A significant improvement of the front metallization was carried out on the last years using the most common industrial screen printing technology.
In this work the print-on-print process has been studied in detail. An efficiency increase of 0.2% abs. was achieved compared to the single-print process. Economical calculation reveals the profitability of this process for solar cell mass production.

Keywords: print-on-print, metallization, screen print, series resistance

1 INTRODUCTION

The reduction of production costs is the main target of solar cell manufactures and new and established technologies are reinvestigated to check the potential to reach this goal.

One of the most discussed techniques is the screen printing process, however, there seems to be no real alternative technologies [1]. The introduction of screens with higher mesh counts and stencil screens keep this technique interesting, as smaller grid width and higher aspect ratios can be achieved. In combination with new metallization pastes and other advantages in the production processes, it is still possible to increase the solar cell efficiency significantly, reduce the production costs and keep the learning curve of silicon solar cells at more than 20%.[2]

The print-on-print process represents one possible step to reduce the cost per W_{peak}, in our investigation the efficiency could be increased by 0.2%, having only slighty higher production costs. In addition improvements in line width (w_L) / aspect ratio (AR) and special designed metallization pastes will drive the efficiency enhancement into new regions.

2 CELL PREPARATION & CHARACTERIZATION

2.1 Solar cell processing

The presented solar cell results are based on a standard industrial back surface field (BSF) solar cell process. The multi crystalline Silicon wafers (p-type, size 6”) were acid-textured and doped with phosphorus. A SiN_x layer was used as antireflection coating. Aluminium paste has been screen printed at the rear side, while a fine line print-on-print process was used on the front side. For the screen printing of the front electrode a stencil screen was used and the grid width changed with the printing step. The second print was aligned to printed fiducials, applied with the step before. The front side busbars were single printed in order to optimize material consumptions. Single print solar cells with the same frontend process sequence were used as a reference. To eliminate the influence of bulk material quality the wafer were neighbouring sorted. The selected wafers were cut of the whole ingot, including the lower-grade bottom part. In accordance to different amount of metallization paste on the front side, the firing peak temperature was optimized for each batch.

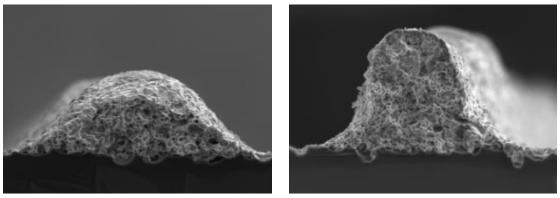
2.2 Characterization

To determine the device parameters different industrial characterization tools were used. The GP Solar 4-Point-Probe was utilized for measurements of line and contact resistance of the printed front grid using transfer length method (TLM) and 4 point measurement.

To identify the geometrical data a Nikon confocal microscope and a contactless multi sensor surface measurement tool (FRT MicroProf®) were used. Both tools accomplish accuracy smaller than 1µm. The Nikon was used to measure the line width for the specific contact resistance (ρ_C) measurement, for each sample 4 - 5 different positions were analysed and fitted at 50 points. These data were used for the exact determination of the contact resistance with TLM method. The information of the volume of the conductor lines, roughness and line width, were measured using the FRT and analyzed by an automatic software tool. For each cell 4 different positions were measured (50 line fits per measurement).

3 RESULTS

The obtained cross section profiles of the two batches differ from each other, as show in Fig. 1. The print-on-print technique (Fig. 1 b) allows high aspect ratio and fine line width. Another advantage is the uniformity of the front grid, thereby a maximum utilization of the printed silver paste is reached. This benefit affords a reduction in shadowing, together with lower line resistance.



a) b)

Figure 1: SEM cross section of contact finger (same magnification) a) standard single-print and b) print-on-print.

3.1 Geometric measurements

The optical measurement of the surface topography shows strong diversifications between both printing techniques.

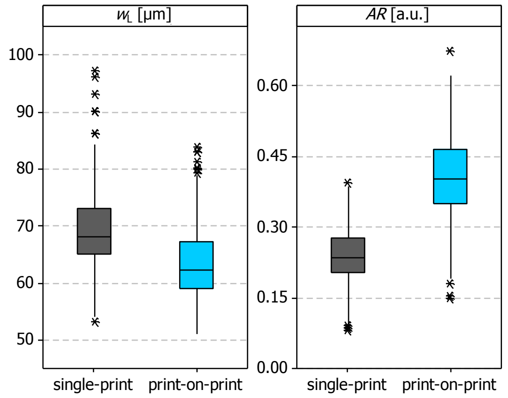


Figure 2: Boxplots showing the w_L (left) and *AR* for single-print and print-on-print metallization.

Figure 2 displays the results of these measurements. Compared to the single-print process, the line width was decreased by 9% (left) or to 63 µm while the *AR* was increased by 70% (right) relatively at the same time for the print-on-print process. The profile changed from a flat Gaussian like to a steeply rising parabolic form having a flat top area (Fig. 3).

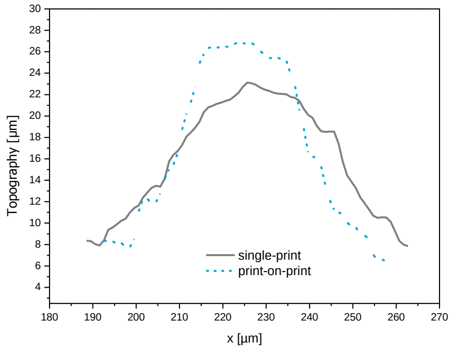


Figure 3: Cross section profile of a single-print and print-on-print contact finger.

All in all the cross section area of the fingers was increased by up to 25% and hence the conductivity of the metallization while the shadowing losses decreased due to narrower gridlines.

3.2 Electric measurements

An important parameter for a high efficiency solar cell is the series resistance (R_S), a sum of mainly bulk resistivity, contact and line resistance. With the trade-off between shadowing and conductivity the front grid takes up over 80% of these. This work pursues the solution by fine line printing with small contact area and high aspect ratio. The experiments have shown that a good contact resistance is the basis for a low R_S. By adjusting the peak firing temperatures for the print-on-print process, contact resistances below 6.5 mΩ/cm² are achievable, shown in Fig. 4. A significant decrease in line resistance of up to 25% was achieved. Due to an improved homogeneity of the print quality, a reduction of the scattering of those values could be observed at the same time. The second print reduced the roughness along the gridline and eliminated interruptions.

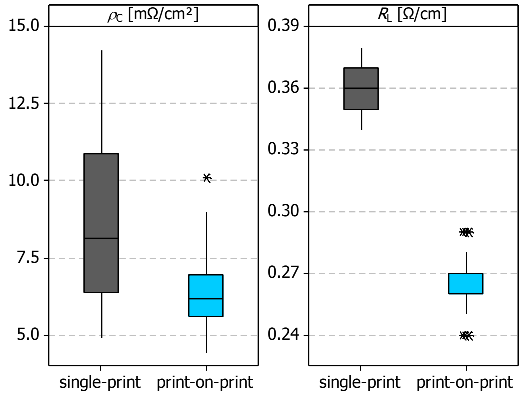
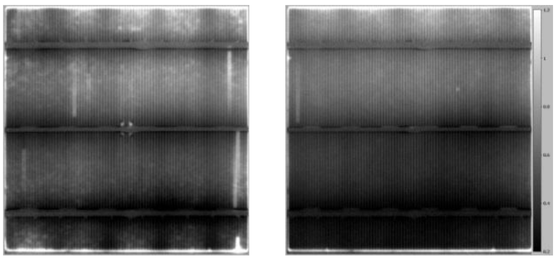


Figure 4: Specific contact resistance (left) and line resistance (right) of single-print and print-on-print grid lines.

The first approach will follow the empirical sense that the contact resistance declines with an approved line width, because of the larger contact area. Otherwise the contact formation is explicit limited by the glass frit [3] which etches the anti-reflection coating. If there is too much glass at the bottom of the grid line, the contact resistance increases. The same result is observed in case of insufficient etching, so that there is still nitride under the contact [4].

The results in Fig. 4 (left) are showing that the print-on-print enhances the electrical contact. One possible reason is the cross section profile. The print-on-print solar cell shows an abrupt steep flank and a homogeneous plateau, in comparison to the more flat single-printed sample (see Fig. 3). Therefore the absolute glass frit amount is more uniform and because of this the firing peak temperature is ideal for an exceeded area.



a) b)

Figure 5: PLRs-Images of a) single-print and b) print-on-print solar cells (equal black/white scale).

Both, the lower line resistance and the better contact resistance can be extracted from the PLRs-Images in Fig. 5. The PLRs image of the print-on-print solar cell (b) shows a very uniform, low resistance in contrast to the single printed solar cell (a), where many local differences can be observed.

In addition the numbers of line interruptions decreases with the print-on-print approach to zero, as it is almost unlikely that an interruption will occur at exactly the same position on both screens.

The improvements in series resistance, together with reducing the shaded area of the solar cell, lead to an efficiency gain of 0.2% absolute for print-on-print compared to single-print process. The distribution of both technologies is nearly the same, due to the different material quality between bottom and top of the ingot (see Fig. 6). The observed improvement in solar cell efficiency is significant and only driven by the front side metallization as the wafers were neighboured sorted and have undergone the same sequence except the front side metallization.

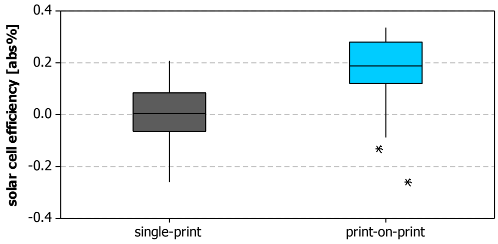


Figure 6: Boxplot revealing the significant enhancement of the solar cell efficiency by the print-on-print process (results from direct comparison of neighboured wafers)

3.3 Further work

The print-on-print technology opens opportunities for new, special designed metallization pastes. Today one paste is used, representing a compromise between contact and line resistance, solderability and amount of silver. In the future it will be possible to use one special contact resistance optimized paste for the first print and a high conductive one for the second printing. This preparation follows a very similar approach as the light induced plating process, where the line and contact resistant can be optimizing [5].

Another approach is the possible enhancement in passivation quality on the front side by the use of busbar metallization paste without or very low percentage of glass frit. As result the antireflection coating/passivation layer is less damaged and the recombination at the front side is reduced. In first experiment a gain in V_{OC} of 2 mV has been observed.

4 ECONOMICAL CONSIDERATION

An important issue for the implementation of a new process with new production equipment is the cost effectiveness. Hence economic calculations were carried out, taking in account the additional equipment and material costs as well as the increased profit due to higher cell efficiencies. All of these are based on module sale price.

Price reduction scenarios of -25% (short-term) and -50% (mid-term) were calculated. With the assumption of today`s common module costs, the breakeven of print-on-print is already reached with a cell efficiency increase of below 0.2% absolutely. Figure 7 advertises the current status of print-on-print, today a profitable operation is expected.

With the usage of a two paste metallization pastes and further R&D work, an increase of up to 0.3% is pretty probable. In addition the yield will be improved due to the better print quality. Furthermore higher module efficiencies are the key for diversification against competitors.

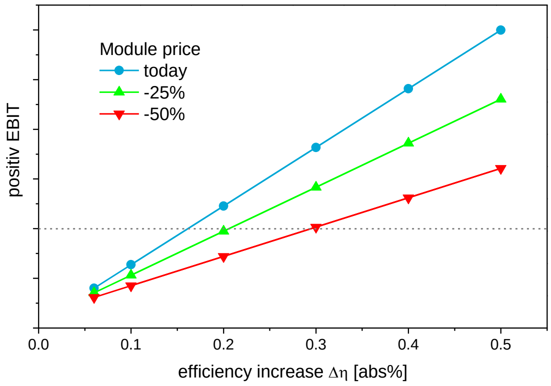


Figure 7: diagram displaying the dependency on acquisition which is generated through the print-on-print process and efficiency enhancement.

Summarizing the advantages of the solar cells and the outlook as well as the EBIT deployment the print-on-print process is still at a point of industrial interest.

5 CONCLUSION

The print-on-print technology was evaluated and optimized at the Q.Cells Reiner-Lemoine Research Center. The efficiency increase of 0.2% is related to the reduced series resistance and higher short circuit current density, produced with nearly the same amount of silver and finer gridlines. Further work will improve this, e.g. by the usage of two different pastes.

The economic calculation reveals that the print-on-print technology is already interesting for industrial mass production as a positive EBIT is expected. Anyway this technology is predestinated to use for high efficiency solar cells to reach new efficiency ranges.

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