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Record low Ag paste consumption of 67.7 mg with dual print

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Abstract

We investigate and compare three different fine line printing techniques for the silver front side metallization of industrial-type silicon solar cells: single print, dual print and print-on-print. We obtain finger heights of 5.6 µm for single print, 9.5 µm for dual print and 15.1 µm for print-on-print as well as finger width between 46.2 µm and 61.3 µm. We process PERC solar cells with dual print and print-on-print. For the dual print, we test two different bus bar designs, a standard rectangular shaped bus bar and a segmented bus bar. The resulting PERC solar cells achieve conversion efficiencies of 19.8% for dual print and print-on-print. The dual print with segmented bus bar design reduces the Ag paste consumption to 67.7 mg, measured after printing prior to drying. To our knowledge, this is the lowest front side Ag paste consumption that has been reported so far. Additionally, we model optimum Ag finger width in dependence of electrical and geometrical parameters. We find that even when assuming very optimistic parameters, the optimum finger width of 26 µm is just a factor of two lower compared to the state of the art technology today.

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Keywords: Screen-printing; Print-on-print; Dual print; Fine line printing; Paste consumption;

1. Introduction

Industrial crystalline Si solar cells typically apply a screen-printed silver (Ag) front contact [1] with paste consumption between 120 mg [2] and 200 mg [3] per wafer. It provides a good conductivity and a well known and stable process. The main targets for further improvement are to increase the efficiency and to reduce the consumption of the expensive Ag paste. One option is to reduce the finger width of the silver front contact in order to reduce the shadowing loss and hence increase the short circuit current density (J_{sc}). However, this may increase

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the finger contact and line resistances. Therefore, fine line printing requires a smooth finger profile in combination with a high aspect ratio of the silver finger.

Among others, three different printing methods for the front Ag fingers are currently investigated in details in both industry and R&D institutes: a standard mesh screen single-print (SP) process, a dual print (DP) process (mesh screen and stencil) [4] and a print-on-print (PoP) process using two mesh screens [5]. The dual print process applies two printing steps and has thereby the advantage to use two different silver pastes for bus bar and the finger grid. In the first step, the bus bars are printed using an optimized mesh screen for lower paste consumption. Then, the fingers are printed with a stencil [6]. A stencil features 100% open area in the aperture, which leads to a benefit of excellent paste transfer efficiency and line height uniformity when compared to a mesh screen's typical 60% open area [7]. The print-on-print process typically uses two mesh screens with different apertures. Only the finger grid is printed in the first step. The second printing step prints the finger grid together with the bus bars and is highly accurately aligned on the first print step [5]. The advanced printing techniques as dual print and print-on-print target to lower the silver paste consumption in combination with increasing the cell efficiency by achieving finer silver finger width while maintain a sufficient finger height in order to reduce both shadowing losses and resistive losses. Previous work on dual print demonstrated finger width down to 75 µm and an efficiency up to 16.6% on multi crystalline wafer [1,8]. In case of print-on-print, finger width down to 63 µm [9] and an efficiency of 18.9% [10] on Cz-Si have been reported. So far, the lowest silver paste consumption of 80 mg dry mass has been obtained by single print achieving efficiencies of to 18.9% [11].

In this paper, we produce PERC solar cells with the fine line printing techniques dual print and print-on-print. In order to achieve high efficiencies with a low Ag paste consumption, we use a non-firing through paste and a segmented design for the bus bars with dual print. In addition, the finger width limitations for screen-printing are estimated by analytical modeling.

2. Comparison of single print, dual print and print-on-print

Ultra-fine wire mesh screen were used for the single print (SP) tests with line opening 40 µm and an emulsion thickness of 13 µm. The mesh count is 380. For dual print, the bus bar screen has a high mesh count of 400 and an emulsion thickness of 10 µm. The investigated nickel stencil has an aperture of 40 µm with 91 fingers. For print-on-print (PoP) the finger grid is printed in the first step and the fingers with bus bars are printed on top in the second step. We test 30/40 µm (first/second print) and 40/50 µm screen apertures. The number of fingers for the 30/40 µm combination is 90 and 81 for 40/50 µm. All silver pastes used in this study are commercial available. We use the same pastes for all three printing approaches and do not apply specific stencil Ag pastes.

The finger x-section profiles obtained with the three different printing techniques using a screen and stencil finger aperture of 40 µm are analyzed with a Hitachi S-4800 scanning electron microscope (SEM). Images of the cross-sectional area of the printed Ag fingers for the three different printing techniques are shown in Fig. 1. The printed finger width ranges between 46 µm and 61 µm. We measure finger heights of 5.6 µm (SP), 9.5 µm (DP) and 15.1 µm (PoP) at the cross-section of the SEM images. Note that although the finger height with DP is lower than that of the PoP, the dual print produces the most conductive Ag finger due to a nearly flat surface profile along the finger length [12].

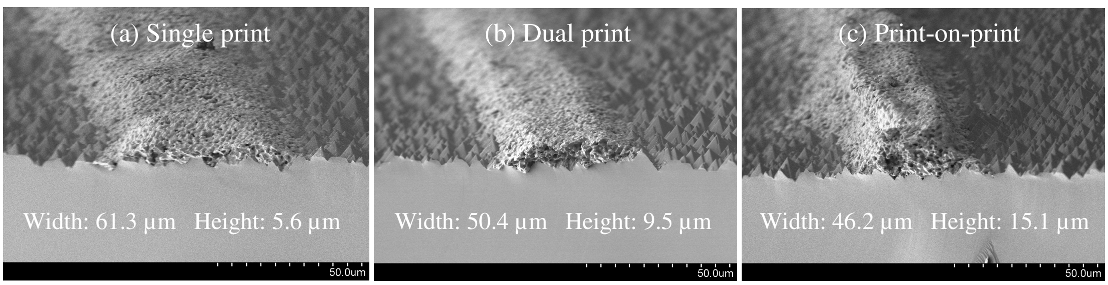

Figure 1: Cross-section images by scanning electron microscopy of wafers printed using (a) single print, (b) dual print and (c) print-on-print.

3. PERC solar cells with dual print and segmented bus bar design

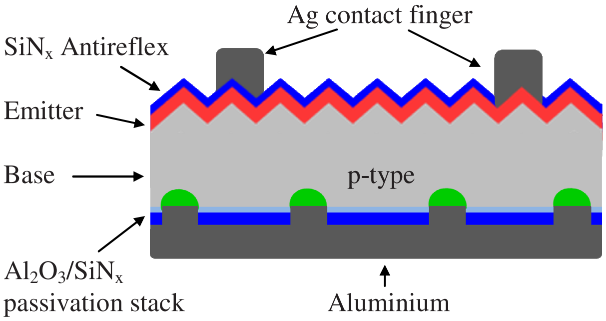

Figure 2: Schematic drawing of the PERC silicon solar cell with screen-printed Ag front and Al rear contacts. We vary the bus bar design as well as the printing technique for the front side grid Ag grid.

We use 156 x 156 mm² large and 180 µm thick p-type Cz silicon wafers with a resistivity of 2 Ωcm. The schematic drawing of the final PERC cell is shown in Fig. 2. The cells get a protection layer on the rear side before texturing in an alkaline batch process. After a homogenously diffused phosphorus emitter of 60 Ω/□ sheet resistivity, the protection layer is removed. The rear side is passivated by an atomic-layer deposited (ALD) Al_2O_3/SiN_x layer stack, whereas the front side is covered with a PECVD SiN_x antireflective layer of refractive index n_{sin} = 2.05 and a thickness of about 70 nm. Then, the rear passivation is locally removed with laser contact opening by ablation (LCO) in order to form line-shaped rear contacts. Further process details are described in Ref. 13. We use a DEK Eclipse printer for the dual print as well as print-on-print of the silver front contact formation. The rear side of the solar cell is full-area Al screen printed. Pastes from Heraeus are used for all printing steps. A drying process in a belt furnace completes each printing step. A firing step in a conveyor belt furnace finalizes the solar cell process.

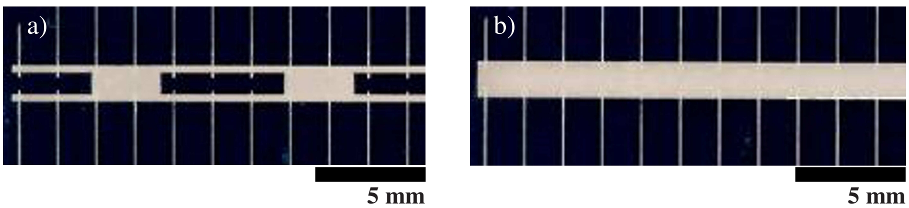

Figure 3: Images of the segmented front side bus bar design (a) and the standard conventional rectangular bus bar design (b).

In an attempt to further save Ag paste consumption, we have redesigned the bus bars for dual print to apply segmented pads, as shown in Fig 3. We adjust the design of the segmented bus bars to the test pins for our IV tester. The segmented bus bar design has 3mm long and 1.5 mm wide pads and the pads are spaced with 5.5 mm distance. The pads are connecting by two lines with a width of 250 µm. The printed area of the bus bars is then reduced by 41%. A PERC solar cell using dual print with such segmented bus bar design achieves a conversion efficiency of 19.8% with open-circuit voltage V_{oc} of 655 mV, short circuit current density J_{sc} of 38.8 mA/cm² and a fill factor FF of 77.8%. The reference cells with print-on-print (40 µm for the bottom, 50 µm for the top print) and dual print using a standard bus bar structure achieved also efficiencies of 19.8%. The measured parameters are shown in table 1. Comparing these three cells, we see a reduced FF and a higher J_{sc} and V_{oc} with lower Ag paste consumption. The root cause of the strong differences of the electrical parameters for the two printing techniques need to be further analyzed. The reference cell with a conventional rectangular bus bar design uses 83.6 mg per cell measured after printing prior to drying, which divides into 52.6 mg for the finger and 31.0 mg for the bus bar print.

The segmented bus bar design has resulted in total Ag paste usage of only 67.7 mg per cell, with 47.0 mg for the finger and 20.7 mg for the bus bar print. Hence, the segmented bus bar design reduces the Ag paste consumption by approximately 30% which is close to the 41% area reduction of the bus bar layout. To our knowledge, the measured 67.7 mg Ag paste consumption per wafer is the lowest front side Ag paste consumption that has been reported so far.

Table 1: Comparison of cell parameters and Ag paste consumption on PERC solar cells with standard and segmented bus bar structures. Pastes from Heraeus are used for all printing steps.

Printing technique	Bus bar design	Ag finger aperture [µm]	*Eta* [%]	J_{sc} [mA/cm²]	V_{oc} [mV]	*FF* [%]	Front Ag paste consumption [mg]
Print-on-Print	Standard	40/50	19.8	37.9	651	79.9	194.1
Dual Print	Standard	40	19.8	38.5	655	78.6	83.6
Dual Print	Segmented	40	19.8	38.8	655	77.8	67.7

4. Finger width limitation of screen-printing

In order to further optimize the cell efficiency, we investigate the finger width limitation of screen-printing in dependence of electrical and geometrical parameters of the Ag finger grid. We made an analysis of the power loss for actual electrical Ag paste parameters as well as for optimized Ag pastes in the future in dependence of the aspect ratio. The following equations 1 and 2 are taken from Ref. 14.

The equation for the power loss fraction p_s due to optical losses is:

$$p_s(s, w_f) = \frac{s \cdot w_{b(UC)} + l_f \cdot w_f}{s \cdot a} \quad (1)$$

The variable parameters are the finger pitch s and the finger width w_f. The finger length of a unit cell l_f is given from the grid design, $w_{b(UC)}$ and a corresponds to the half of the bus bar width and the length of the unit cell, respectively. The unit cell in our case with three bus bars is given by the half the separation distance times the finger length of the grid divided by 6. Shading losses will decrease with increased finger pitch as well as with reduced finger width. However, *e.g.* a larger finger pitch will increase losses due to the emitter resistance.

The power loss fraction p_e due to resistive losses can be expressed by:

$$p_e(r) = \frac{J_{mpp} \cdot r}{V_{mpp} + r \cdot J_{mpp}} (1 - p_s) \quad (2)$$

Here, V_{mpp} and J_{mpp} are the voltage and current at the maximum power point, r is the sum of the emitter resistance, contact resistance and finger resistance. Other resistance fractions are not taken into account as they are independent of the variable screen-printed parameters. The total loss p is the sum of the electrical p_e and the optical p_s loss fractions. In order to minimize the total losses in the solar cell, an optimum between optical and electrical losses needs to be found. Loss calculations have been performed for a homogenous emitter sheet resistance of 70 Ω/□ on a 156 x 156 mm² large solar cell. For each point of the finger width, the optimum finger pitch is chosen. The results are shown in Fig. 4a) and b). One percent absolute in the total power loss corresponds to one percent relative in the efficiency.

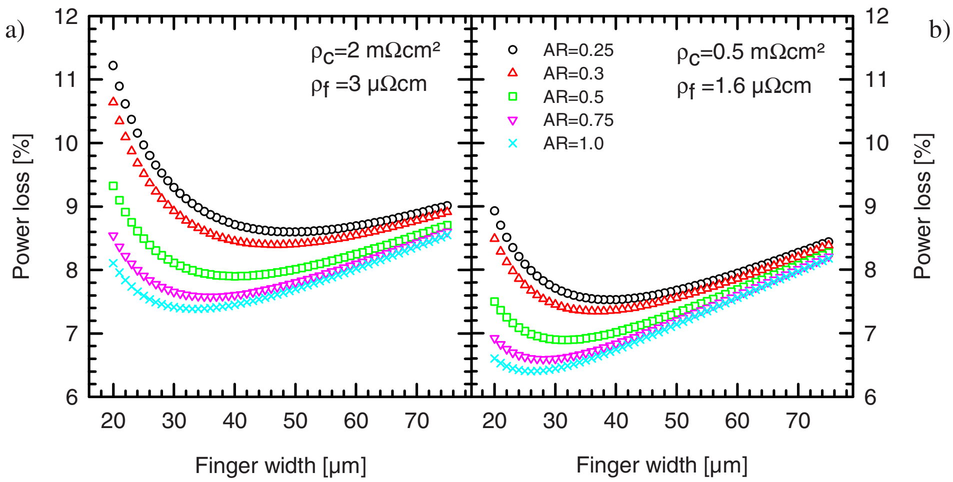

Figure 4: Power loss of a solar cell versus the finger width: (a) variation of the aspect ratio (height divided by width) of the Ag finger assuming specific contact resistance ρ_c and specific line resistance ρ_f parameters of a state of the art Ag paste (b) variation of the aspect ratio assuming very optimistic values of ρ_c and a specific line resistance ρ_f of pure Ag for a future Ag paste.

In the first case, the assumed electrical parameters for a state of the art Ag paste are 2 mΩcm² for the specific contact resistance ρ_c and 3 µΩcm for the specific line resistance of Ag metallization ρ_f. The variable parameter is the aspect ratio (AR) of the silver finger which is the ratio between the finger height and finger width. The starting point for the AR is chosen at 0.25 as obtained for dual print as shown in Ref. 12. This AR results in a minimum power loss of p=8.60% achieved at w_f=49 µm. For a very optimistic AR of 1, the optimized finger width is calculated to w_f=33 µm with p=7.39%. Fig 4b shows the same calculations assuming very optimistic values of the conductivity and contact resistance for potential future Ag pastes. Here, the assumed electrical parameters are ρ_c =0.5 mΩcm² and ρ_f =1.6 µΩcm. The assumed specific line resistance of Ag metallization is the limit for pure Ag. The calculations show a high potential for decreasing the total power loss with reduced finger width. The AR of 0.25 results in a minimum power loss of 7.53% at w_f=39 µm. A combination of the geometrical and electrical improvements leads to a minimum power loss of p=6.40% at a finger width of 26 µm, assuming an AR of 1.

5. Conclusions

We have compared dual print (DP) and print-on-print (PoP) for PERC solar cells. The PoP process achieves conversion efficiencies up to 19.8% with a high fill factor of 79.9%. The Ag paste consumption for the front side is 194.1 mg. The DP process applies two printing steps and has thereby the advantage to use two different silver pastes for bus bar and the finger grid. In addition, we design a segmented bus bar screen for dual print to further reduce the Ag paste consumption. With the combination of dual print and the segmented bus bar design, we achieve also a conversion efficiency of 19.8% with the lowest front side Ag paste consumption of 67.7 mg that has been reported so far to our knowledge. Comparing the segmented bus bar with a conventional rectangular bus bar design, we can reduce the Ag paste consumption after printing prior to drying by 30% for the bus bar print. By analytical modeling, we explore the finger width limitations of screen-printing. When using a today's state of the Ag paste, we obtain an optimum finger width of 33 µm assuming ideal printing capabilities. Assuming additionally very optimistic future Ag paste improvements, the optimum finger width reduces to w_f=26 µm.

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