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ScienceDirect

Energy Procedia 38 (2013) 725 – 731

Energy Procedia

SiliconPV: March 25-27, 2013, Hamelin, Germany

Fineline printing options for high efficiencies and low Ag paste consumption

Helge Hannebauer[a,]*, Thorsten Dullweber[a], Tom Falcon[b], Rolf Brendel[a,c]

[a]*Institute for Solar Energy Research Hamelin (ISFH), Am Ohrberg 1, D-31860 Emmerthal, Germany*
[b]*DEK Solar, 11 Albany Road, Weymouth, DT4 9TH, U.K.*
[c]*Department of Solar Energy, Institute of Solid-State Physics, Leibniz University of Hanover, Appelstrasse 2, D-30167 Hanover, Germany*

Abstract

In this paper, 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 produce solar cells using the same screen or stencil aperture of 40 µm and about 92 fingers and obtain finger widths below 60 µm for all three approaches. The print-on-print process achieves the highest finger heights of 20 µm after firing but with quite strong finger height variation. In contrast, the dual printed fingers have a very flat surface with a finger height of 14.5 µm which leads to the highest cross-section area of 530 µm² of the three techniques. The single print shows the lowest cross-section area of 390 µm² due to the lowest average finger height. The measured finger line resistance correlates with the finger cross-section area. The dual print allows us to use a non-firing through bus bar paste which increases the V_{oc} by 2 mV and hence achieves the highest efficiency of 19.1% using full-area Al-BSF cells. Due to an optimized bus bar screen print in combination with only 30 µm finger aperture, the dual print has the lowest Ag paste consumption of only 75 mg/wafer, one of the lowest Ag paste consumption that has been reported so far. A first batch of PERC solar cells with dual-printed Ag front contacts shows efficiencies up to 19.6%.

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

* Corresponding author. Tel.: +49-5151-999-637; fax: +49-5151-999-400.
E-mail address: hannebauer@isfh.de.

doi:10.1016/j.egypro.2013.07.339

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 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 process (mesh screen then stencil) [4] and a 'print-on-print' process using two mesh screens [5]. The dual print (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 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 (PoP) 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 gain up to 0.4% absolute [1,8]. In case of print-on-print, finger width down to 63 µm [9] and an efficiency of 18.9% [10] have been reported. With silver paste consumption of only 80 mg dry mass, an efficiency of 18.7% has been demonstrated [11] with single print.

In this paper, we compare the three different printing techniques single print, dual print and print-on-print and investigate their impact on the finger profiles, the finger line resistance and the conversion efficiency of full-area Al-BSF cells as well as PERC cells.

2. Experimental setup

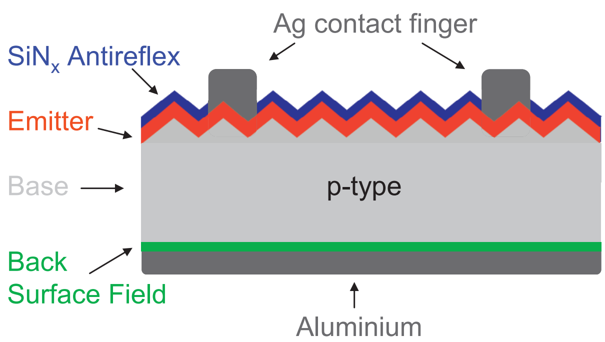

Fig. 1. Schematic drawing of the industrial type silicon solar cell with screen-printed Ag front and Al rear contacts. We vary the printing technique for the front side grid Ag grid.

Ultra-fine wire mesh screens were used for the single print (SP) tests with line openings from 80 µm down to 30 µm. The mesh count varies between 300 and 380. For the optimization of Ag paste consumption and conversion efficiencies, we vary the emulsion thickness. Using a screen aperture of

30 µm, emulsion thicknesses between 4 and 15 µm are tested. For 40 µm line opening, an emulsion thickness between 6 and 17 µm is used. The numbers of fingers go from 118 for 30 µm and 94 for 40 µm down to 70 for 80 µm screen aperture. For dual print, the bus bar screen has a high mesh count of 400 and an emulsion thickness of 10 µm. The investigated nickel stencils have apertures of 30 and 40 µm with 107 and 91 fingers, respectively. 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), 40/50 µm and 50/60 µm screen apertures. The number of fingers for the 30/40 µm combination is 90 and 81 for 40/50 µm. The 50/60 µm PoP combination has 76 silver fingers and thereby the same as the tested 60 µm SP screen. 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.

For the full-area Al-BSF solar cells, we use 156 x 156 mm² 180 µm thick p-type Cz silicon wafers with a resistivity of 2 Ωcm. The schematic drawing of the final solar cell is shown in Fig.1. After cleaning, the wafers are textured on both sides in an alkaline batch process. A PECVD SiN_x antireflective layer of refractive index n_{sin} = 2.05 and a thickness of about 70 nm passivates a homogeneously diffused phosphorous emitter of 60 Ω/□ sheet resistivity. We use a DEK Eclipse printer and three different printing techniques described above for the front contact formation. The rear side of the solar cell is full-area Al screen printed. A drying process in a belt furnace completes each printing step. A firing step in a conveyor belt furnace followed by laser edge isolation finalizes the solar cell process.

3. Analysis of printing results

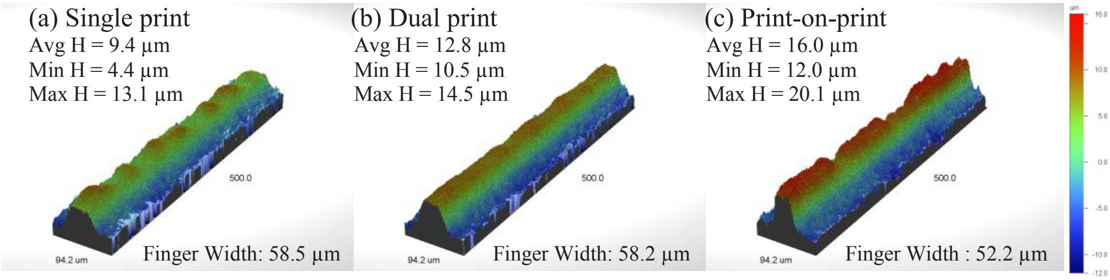

Fig. 2. Finger profiles measured with an optical profilometer printed using (a) single print, (b) dual print and (c) print-on-print. "H" denotes the measured finger height.

To compare the single print (SP), dual print (DP) and print-on-print (PoP), we process solar cells using a screen and stencil finger aperture of 40 µm and 90 to 94 fingers per wafer for all three printing techniques. In Fig.2 the finger profiles measured with a Wyko NT9100 optical profilometer are shown. We achieve finger widths of 59 µm (SP), 58 µm (DP) and 52 µm (PoP). We calculate the cross-section area A by integrating the area below the finger profile for three points in figure 2. The three points are chosen at a high, a low and a middle finger height. We obtain average cross-section areas of 390 µm² (SP), 530 µm² (DP) and 490 µm² (PoP).

In addition, we measure the finger line resistance R_L on final solar cells for the three printing techniques. The R_L values are obtained by cutting a 2 cm wide stripe out of the wafer and then measure the voltage drop across a silver finger. The error bars from Fig. 3 refer to the standard deviation of the measurements at different points for the cross-section area and at different silver fingers for the line resistance. The dual print achieves the lowest line resistance of 0.5 Ohm/cm which correlates to the highest cross-section area (Fig. 3). The PoP has a slightly higher line resistance due to the smaller cross-section area. SP has the lowest finger height and therefore the lowest cross-section area and the highest line resistance of these three printing methods. We fit the experimental data in Fig. 3 by using the equation $R_L=\rho/A$ and obtain a value of $2.7*10^{-6}$ Ωcm for the paste resistivity which agrees well with the specification from the data sheet of the paste.

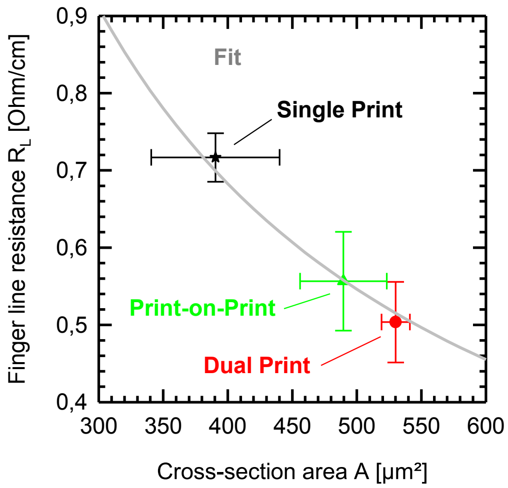

Fig. 3. Finger line resistance vs. average finger cross section area for the three printing techniques using the same Ag paste. The experimental data are fitted using the equation $R_L=\rho/A$.

4. Solar cell results

We apply the three different printing techniques to solar cells with full-area Al-BSF and measure the Ag paste consumption after printing prior to drying. The conversion efficiencies as well as the fill factors (*FF*), the short circuit current densities (J_{sc}), and the open circuit voltages (V_{oc}) versus the silver paste consumption are shown in Fig. 4a-d for single print (SP), dual print (DP), and print-on-print (PoP). The solar cells with a non-optimized SP show a strong reduction of the conversion efficiency with reduced Ag paste consumption since the reduced finger width causes many finger interruptions which lower the FF. With increasing the emulsion thickness for SP, the finger interruptions reduce and we obtain an efficiency of 18.5% for a paste consumption of 90 mg/wafer. The print-on-print process achieves up to 18.8% efficiency for a Ag paste consumption of 182 mg/wafer when using screen apertures of 50 µm for the bottom and 60 µm for the top print. The dual print combines the highest efficiencies with the lowest silver paste consumption. Using a stencil aperture of 40 µm results in 96 mg/wafer paste consumption and an efficiency of 18.9%. However, the best efficiency of 19.1% is achieved with DP using a stencil aperture of 30 µm with a paste consumption of only 75 mg/wafer. The total paste consumption divides into 41 mg for the finger and 34 mg for the bus bar print. The high efficiency is due to the high J_{sc} of 37.6 mA/cm² and V_{oc} of 642 mV.

We investigate the improvement of V_{oc} for dual print by comparing the impact of firing-through versus non-firing-through silver pastes. We observe an average V_{oc} increase of 2 mV with the non-firing-through bus bar paste as shown in Fig. 5. This is caused by a reduction of the total emitter saturation current densities $J_{0e,total}$ due to a reduced area of metal contacted emitter.

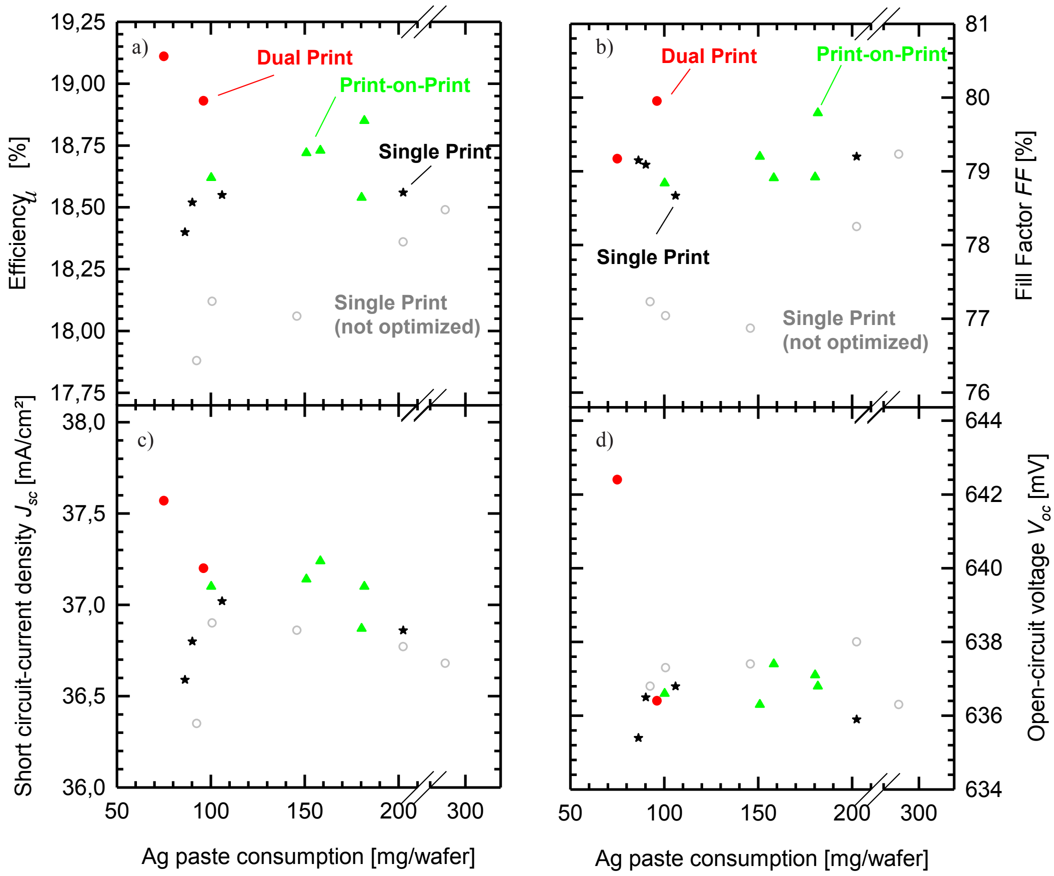

Fig. 4. Electrical parameters of different printing techniques versus silver paste consumption: (a) efficiency, (b) fill factor, (c) short circuit current density Jsc, (d) open circuit voltage.

The emitter saturation current densities J_{0e} in Ref. 12 allow a prediction of the total $J_{0e,total}$ for firing-through versus non-firing-through bus bar pastes assuming an area coverage f of the Ag screen-printed metallization using the following equation:

$$J_{0e,total} = f * J_{0e,met} + (1-f) * J_{0e,pass} \quad (1)$$

For an homogeneously diffused emitter sheet resistance of 60 Ω/sq and an area coverage f of 6% with the firing-through paste B, we obtain a total emitter saturation current density $J_{0e,total}$ of 140 fA/cm² using the equation (1) with $J_{0e,met}$ = 450 fA/cm² and $J_{0e,pass}$ = 120 fA/cm² from Ref. 12. Assuming an area coverage of 3% for the bus bar metallization and thereby a Ag metallized area of 3%, we obtain $J_{0e,total}$ = 130 fA/cm² by applying equation (1). The calculations above demonstrate that using a non-fired through bus bar paste C for dual print potentially reduces the $J_{0e,total}$ by almost 10 fA/cm² which corresponds to a V_{oc} improvement of 1 mV depending on the additional contributions of the bulk and rear saturation current densities.

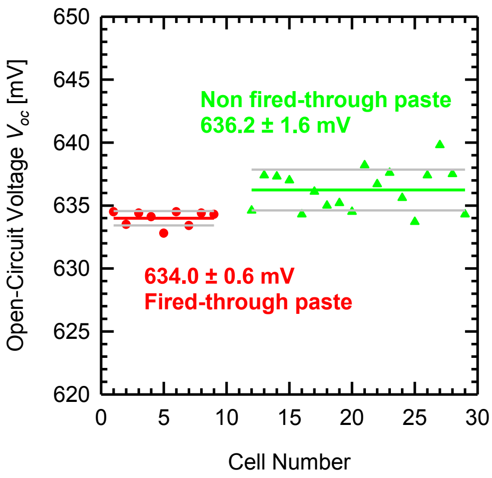

Fig. 5. Influence of non-fired through paste using for bus bars on the V_{oc} for the dual print process.

5. PERC solar cells with dual print

As a precursor to further development, we process passivated emitter and rear cells (PERC). However, these cells get a protection layer on the rear side before texturing. After the phosphorus diffusion, 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 the same antireflective layer as for the full-area Al-BSF solar cells. 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 the dual print metallization technique for the front side of the PERC cells. The rear side of the solar cell is full-area Al screen printed. In a first batch, a PERC solar cell using dual print achieves a conversion efficiency of 19.6% with V_{oc} of 651 mV, J_{sc} of 38.8 mA/cm² and a *FF* of 77.7%.

6. Conclusions

We have compared single print (SP), dual print (DP) and print-on-print (PoP) for industrial type silicon solar cells. The PoP process achieves finger width of 52 µm and the highest finger heights of 20 µm. The surface of the finger profile has a quite strong finger height variation. In contrast, the dual printed fingers have a very flat surface with a finger height of 14.5 µm which leads to the highest cross-section area of 530 µm² of the three techniques. The SP process shows the widest contact fingers of 59 µm and the lowest cross-section area of 390 µm² due to the lowest average finger height. We find a correlation between the measured finger line resistance and the finger cross-section area. 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. When using a non-firing through bus bar paste, the V_{oc} increases by 2 mV and we achieve the highest efficiency of 19.1% using full-area Al-BSF cells. Also, due to an optimized bus bar screen print in combination with only 30 µm finger aperture, the dual print has the lowest Ag paste consumption of only 75 mg/wafer, one of the lowest Ag paste consumption that has been reported. In a first batch, a PERC solar cell using dual print achieves a conversion efficiency of 19.6% with V_{oc} of 651 mV, J_{sc} of 38.8 mA/cm² and a *FF* of 77.7%.

Acknowledgements

The authors thank S. Wyczanowski and U. Baumann for sample and solar cell processing. This work was supported by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety under Contract No. 0325296 in cooperation with SolarWorld Innovations GmbH, RENA GmbH, SINGULUS TECHNOLOGIES AG and Heraeus Precious Metals, which is gratefully acknowledged. We thank Heraeus, DuPont and Ferro for providing with pastes for this study.

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