Solar Energy Materials and Solar Cells 180 (2018) 83–90

Contents lists available at ScienceDirect

Solar Energy Materials and Solar Cells

journal homepage: www.elsevier.com/locate/solmat

Front side metallization of silicon solar cells by direct printing of molten metal

B. Gerdes[a,*], M. Jehle[a], N. Lass[a], L. Riegger[a], A. Spribille[b], M. Linse[b], F. Clement[b], R. Zengerle[a], P. Koltay[a]

[a] Laboratory for MEMS Applications, IMTEK - Department of Microsystems Engineering, University of Freiburg, Germany
[b] Fraunhofer Institute for Solar Energy Systems (ISE), Heidenhofstr. 2, 79110 Freiburg, Germany

ARTICLE INFO

Keywords:
Silicon solar cell
Front side metallization
Non-contact printing
Paste consumption
Metal printing

ABSTRACT

In this work, a new approach for the front side metallization of silicon solar cells is presented. Molten solder (Sn96Ag3Cu) is directly printed in a non-contact manner on solar cell precursors via StarJet technology. The StarJet technology features a pneumatically driven, heatable printhead with a reservoir of molten metal and a star-shaped silicon nozzle chip. Using this printhead, a jet of molten metal with 55 µm ± 5 µm diameter is generated and used to apply busbars as well as contact fingers on prefabricated electroplated seed layers. After deposition via StarJet, printed fingers have a minimum width of 70 µm and a mean aspect ratio of 0.94. The printed metallization is evaluated optically and electrically. Aluminum back surface field silicon solar cells with front side electroplated NiAg seed layers and StarJet metallization (busbars and fingers) show efficiencies of up to 18.1% after degradation. Solder is about 30–40 times cheaper than silver and therefore may allow cost-efficient solar cell metallization. The StarJet metallization on electroplated NiAg seed layers is fully functional and requires no additional post-processing steps. Only 6 mg of Ag per cell are consumed for the seed layer. As a proof-of-principle, a module is demonstrated, which consists of four solar cells that are metallized via StarJet.

1. Introduction

In the production of silicon solar cells, Ag pastes used for screen printing of the front side grid are the highest non-silicon cost factor and availability of silver will eventually become a critical factor in solar cell mass production [1,2]. It is therefore desirable to reduce the amount of silver in the front side grid of solar cells to a minimum. This can either be achieved by using printing techniques that reduce the amount of silver pastes or by applying alternative metallization processes that require no silver at all.

Optimized screen printing or stencil printing of narrower fingers with higher aspect ratio can decrease the amount of silver pastes [3,4]. Currently, the paste consumption can be reduced to 65–75 mg/cell by these printing processes, whereas standard consumptions can reach 110 mg [5–8]. Moreover, there are a number of different printing processes for Ag pastes [9–11] and Ag inks [12] available.

An alternative metallization process is a two-step front side metallization, comprising a thin, so-called seed layer that forms the electrical contact, which is then augmented by a main conduction material. These seed layers are typically fabricated and augmented by electroplating. They can also be screen-printed as thin silver paste layers. Two-step metallizations are a promising approach [13] and offer the possibility to use low-cost materials for front side metallization. Therefore, the amount of silver is expected to be significantly reduced in the near future [14].

In this work, tin (solder) is used for contact augmentation, which is, depending on the commodity price, about 30–40 times more cost-efficient than silver regarding material cost [15,16] and shows sufficient electrical conductivity. Please refer to section “Cost of ownership calculation” for a more detailed cost analysis of the process. The StarJet metallization requires about 180 mg for the metallization of one cell. Compared to silver pastes that mainly consist of silver powder, the use of solder can present a substantial cost reduction. However, instead of contact augmentation by electroplating, the solder front side metallization applied and analyzed in this work is directly printed from molten metal in a non-contact process. The printing system is based on the StarJet technology that features a pneumatically driven printhead with a reservoir of molten metal and a star-shaped silicon nozzle chip [17]. The printhead is used to eject jets of molten metal with diameters down to 50 µm to print fingers with 70 µm minimal width. These jets are generated in a continuous manner and do not exhibit Rayleigh breakup under the investigated operation conditions. The printhead features one

* Corresponding author.
E-mail address: bjoern.gerdes@imtek.de (B. Gerdes).

https://doi.org/10.1016/j.solmat.2018.02.022
Received 11 May 2017; Received in revised form 12 February 2018; Accepted 13 February 2018
0927-0248/

Table 1
Subgroups of precursors in group 1 and Ag amount in seed layer.

Subgroup	Screen printed fingers (fully functional)	Screen printed bus bars (fully functional)	Seed layer finger	Seed layer bus bar	Total amount of Ag
a	88 mg			15 mg	103 mg
b		17 mg	14 mg		31 mg
c			14 mg		14 mg

nozzle which is positioned over the solar cells and moved with 950 mm/s during direct printing of the front side metallization. The StarJet technology thus substitutes the expensive Ag by solder and the directly printed metallization does not require any post-processing. To our knowledge, direct printing of molten metal is published here for the first time as a means of processing the front side metallization of silicon solar cells.

2. Materials and methods

2.1. Solar cell precursors

Different precursor groups were processed to evaluate the StarJet metallization on various materials. Cz-Si Aluminum back surface field (Al-BSF) solar cells in the size of $156 \times 156\,mm^2$ with three busbars and 100 fingers were divided in two groups. For group 1, a fine seed layer of Ag was screen printed and fired. The group is subdivided (Table 1) to evaluate the printing of fingers and busbars independently. To achieve this, solar cells were processed with fingers fully screen printed and busbars pre-processed as low-conductive seed layers (subgroup a). Additionally, solar cells were processed with fingers as pre-processed seed layers and screen-printed fully functional busbars (subgroup b). The third subgroup features fingers and busbars as low-conductive seed layers (subgroup c). Standard industrial silver paste was used and fired in an industrial belt furnace set at a peak-temperature of 880 °C. Table 1 shows the amount of Ag used for processing the front side metallization before the StarJet technology is applied to augment the seed layers.

Group 2 comprises the same $156 \times 156\,mm^2$ Cz-Si Al-BSF material but in contrast to group 1, no screen printing process is used. Instead, the anti-reflection coating is locally opened by laser ablation with a pulsed UV femtosecond laser. The width of the ablated structure amounts to 28 µm. This group is divided in two subgroups as shown in Table 2.

For subgroup a, the anti-reflection coating is only opened by the laser (no seed layer) and for subgroup b the laser ablated precursors are further processed by adding an electroplated NiAg seed layer that contains 10 mg Ni and 6 mg Ag.

2.2. Experimental setup

The pneumatically actuated StarJet-based printhead features a heatable printhead with a reservoir of molten solder. The printhead was previously used to print metal microdroplets and microstructures by applying short pressure pulses of a few ms to the reservoir or in a continuous mode where droplets are printed at a rate of up to 11 kHz [18–21]. A star-shaped silicon nozzle chip, fabricated by deep-reactive ion etching, is mounted below the outlet of the heated reservoir. Fig. 1 shows a schematic sketch of the printhead and a SEM image of a nozzle chip. The star-shaped geometry of the chip orifice confines the droplets and jets in the center of the nozzle by capillary forces, leaving the rinse gas channels open (cf. Fig. 1). During the printing process, the molten metal is only in contact with the tips of the star shaped orifice. The system features two independent pressure regulators for the actuation gas (p_{act}) that is applied to the molten metal in the reservoir and rinse gas (p_{rinse}) that is applied to the rinse gas channels. Nitrogen is used as rinse and actuation gas because of its inert nature. The actuation gas is controlled by a solenoid 3/2-way valve (*MHE2-MS1H-3/2G-M7-K, Festo, Germany*) and is used to apply pressure to the reservoir of molten metal, pushing metal through the nozzle to establish the jet. Meanwhile, the rinse gas flows constantly through the bypass channels of the chip. It prevents the molten metal jet from oxidation. Fig. 1 shows the StarJet silicon nozzle chip with the star-shaped orifice in the middle of the chip and the bypass channels for the rinse gas surrounding it. Nozzle chips are interchangeable and feature different orifice diameters from 60 to 200 µm. For the results shown in this paper a nozzle orifice diameter of 60 µm was used. Applying pressure pulses at pressures larger than 500 mbar for more than 50 ms, depending on chip orifice diameter, leads to the formation of a molten metal jet.

For processing solar cells, the printhead and the valve are mounted in a modified industrial printing platform (*Spectrum II 910, Nordson Asymtek, USA)*. The platform allows for *xy*-displacement of the printhead with up to 1.0 m/s at a precision of ± 35 µm. It features an integrated hotplate, used to heat up substrates during metallization, a height sensor and a camera for positioning of the printhead. The printing platform is used to control the valve for the actuation gas pressure and external electronics are used to power the heater. The printing system is shown in Fig. 2.

A displacement velocity of at least 950 mm/s for moving the printhead is necessary to print lines with homogeneous width. At slower displacement velocities so-called bulges occur due to minimization of free surface energy of the molten metal. This leads to inhomogeneous and unstable lines. The phenomenon is already well known and studied for inkjet printed lines built up from individual droplets of water-based liquids [22]. The effect occurs similarly for molten metal lines printed from a stable jet on a Cz-Silicon wafer heated to 180 °C. However, the surface tension of molten solder is about one order of magnitude higher than the surface tension of water [23]. Therefore, not only bulges occur, but the molten metal forms droplets in the printed line. Fig. 3 shows a picture of a printed grid of lines on a silicon wafer exhibiting bulges and droplets due to low printhead displacement velocities (350 mm/s) and lines printed at 950 mm/s, showing a homogeneous width and no bulges. The line width amounts to 70 µm on a plain silicon surface when a jet width of 50 µm is used for printing.

Table 2
Subgroups of precursors in group 2 and Ag amount in seed layer.

Subgroup	Laser ablation without seed layer	Laser ablation and electroplated NiAg seed layer	Total amount of Ag
a	0 mg		0 mg
b		6 mg	6 mg

2.3. Processing of solar cells

For processing the metallization of busbars and fingers of solar cells the printhead is heated to 320 °C which is about 100 °C above the melting point of the specific solder (Sn96Ag3Cu). The solar cells are heated up to 180 °C by the integrated hotplate. This increases the adhesion of the molten metal to the seed layer significantly. Without heating, the metal jet solidifies and thus shrinks instantly after printing, consequently losing contact to the seed layer. A nozzle chip with an orifice diameter of 60 µm is used. Pressures of $p_{rinse} = 700$ mbar and $p_{act} = 600$ mbar are required to create a stable jet. Fig. 4 shows a picture of a jet as it is ejected from the nozzle orifice. For better visualization, a jet from a nozzle chip with larger diameter of $d_{orifice} = 183$ µm is displayed in Fig. 4. For the metallization of solar cells, a nozzle chip with smaller orifice diameter ($d_{orifice} = 60$ µm) is used to print jets of $d_{jet} = 50$ µm.

The printing height of the nozzle above the solar cells amounts to