Solar Energy Materials & Solar Cells 142 (2015) 18–23

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

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

Progress in fine-line metallization by co-extrusion printing on cast monosilicon PERC solar cells

L. Philipp Richter [a,*], Gerd Fischer [a], Lamine Sylla [a], Melanie Hentsche [a], Stefan Steckemetz [a], Matthias Müller [a], Corie L. Cobb [b], Scott E. Solberg [b], Ranjeet Rao [b], Scott Elrod [b], Phedon Palinginis [a], Eric Schneiderlöchner [a], D. Holger Neuhaus [a]

[a] SolarWorld Innovations GmbH, Berthelsdorfer Str. 111A, 09599 Freiberg, Germany
[b] PARC, a Xerox Company, 3333 Coyote Hill Road, Palo Alto, CA 94304, USA

A R T I C L E I N F O

Article history:
Received 8 April 2015
Received in revised form
8 May 2015
Accepted 14 May 2015
Available online 17 July 2015

Keywords:
Alternative metallization
Fine-line metallization
Co-extrusion
Dual print
Screen-print
Stencil print
Dispensing
High aspect ratio
Efficiency gain
Cast mono

A B S T R A C T

In this paper, we present our progress in co-extrusion printing for fine-line metallization. With this technique, 30 μm wide and 20 μm tall front grid fingers are currently printed. Applied to industrial size cast silicon PERC solar cells, a world record conversion efficiency of 21.42% has been demonstrated. This result was achieved with a production-ready co-extrusion printer that runs at a throughput of 2700 wafers per hour. Furthermore, a printhead is presented that has been developed to enable co-extrusion printing on pseudo-square wafers. Finally the cost advantage of the technology is discussed.

1. Introduction

With front and rear-contacted solar cells exceeding 20% cell efficiency in industrial production, fine-line metallization techniques are becoming even more important in order to further increase the efficiency of crystalline silicon solar cells. They will play a key role in achieving efficiencies beyond 24% with *p*-type Passivated Emitter and Rear (PERC) solar cells without the use of *n*-type Inter-digitated Back-Contact (IBC) or heterojunction cell architecture. Achieving this level of cell efficiency is predicted by Min et al. [1] to be possible solely by continuously improving existing fabrication technologies and *p*-type wafer materials. One way to work towards this goal is to reduce the shading due to the front grid fingers, which is currently about 3–4% without busbars. This shading percentage will increase even further with higher resistivity emitters, which require reduced finger spacing and more fingers. A simultaneous reduction of the front grid shading can only be achieved with a significant reduction of the front finger width.

In order to challenge the incumbent screen-printing technology, novel fine-line metallization techniques will have to meet all the advantages which come along with screen-printing; the latter has demonstrated over the past few years to be both cheap and reliable, and it uses fire-through pastes which are commercially available worldwide. The new technique will also need to be compatible with the anticipated future use of copper pastes. The biggest challenge for a novel fine-line metallization technique is to achieve narrower lines than current screen-printing (< 50–70 μm average finger width) while demonstrating very low optical losses at lower cost. For upgrading print lines in existing factories, the new technique needs to be capable of seamless production line integration.

Furthermore, it can be assumed that a selective emitter will be utilized to contact high resistivity emitters with a sheet resistance beyond 150 Ω/□ [1]. This includes the requirement of a very high alignment accuracy of the fine-line fingers to the selective emitter pattern.

An alternative fine-line metallization technique which is currently under development is stencil printing. In this dual print approach, the busbars are printed with standard screen-printing

* Corresponding author. Tel.: +49 3731 301 1909.
E-mail address: philipp.richter@solarworld.com (L.P. Richter).

http://dx.doi.org/10.1016/j.solmat.2015.05.023
0927-0248/

and dried before a metal stencil is used for finger printing [2]. In a production environment, stencil printing is so far hindered by low optical yields due to bad sealing between the stencil and the solar cell when particles are present on the surface. Additionally, there is the challenge that silicon pieces from broken wafers can easily cut the expensive stencils what would cause uptime problems in manufacturing and increase production cost.

Another approach to printing fine front side fingers is dispensing as presented by Pospischil et al. [3]. A screen-printing-like paste is extruded through a nozzle onto the substrate. This technique is currently in a prototyping stage with a 10-nozzle printhead. From our experience it is challenging to print homogeneous and accurately positioned grid finger ends and achieve sufficient process robustness with this approach.

This paper describes the progress of the previously introduced co-extrusion print technology [4], which is a technology that can go beyond screen-printing and meet all of the aforementioned requirements.

2. Materials and methods

2.1. Cast monowafer material

The cells printed in the following experiments are based on cast mono-crystalline silicon wafers produced at SolarWorld Innovations GmbH. This process for the directional solidification of silicon ingots was originally proposed by Stoddard et al. [5]. Since it produces high quality material at a low production cost (ingot casting), it is very attractive for the photovoltaic industry. The challenge of this process is the minimization of the dislocation density in the silicon, which is on the order of $10^4\,cm^{-2}$ in our material.

As monolithic seed plates are not available in industry standard size crucibles, split seeds are one option that can be used. The arrangement of these seeds, their surface preparation, and their crystallographic quality has been optimized for manufacturing the cast monocrystals used in this work [6].

In order to measure the effective excess-carrier lifetime of the material used for the following experiments, RCA clean and an AlOx passivation was done at ISFH with several 1 Ω cm wafers of this type. The QSSPC method was applied in order to measure the effective excess-carrier lifetime. The value obtained at an excess-carrier injection level of $1 \times 10^{15}\,cm^{-3}$ is about 1 ms (Fig. 1), which is an equal or even better value compared to silicon wafer material grown with the Czochralski process. This demonstrates the high quality of the produced cast monowafer material.

2.2. PERC cell process

Co-extrusion printing has been applied to PERC solar cells [7] with the following properties: $156 \times 156\,mm^2$ *p*-type wafers from cast monosilicon [8], an as-cut thickness of 180 μm, and 1–3 Ω cm resistivity. Saw damage removal and texturing were done using alkaline solutions. The front side anti-reflection coating used within our cell process is a standard PECVD silicon nitride. The high-resistivity $POCl_3$ diffusion process was optimized in terms of production feasibility and high electrical performance. A 300 μm wide Laser-Doped Selective Emitter (LDSE) region was created to ensure a low contact resistance to the front side metallization. The rear side passivation stack is optimized with respect to low surface recombination velocity S_{pass} and high internal reflection. After application of the front side metallization by co-extrusion, the firing conditions have been optimized for this cell type.

2.3. Co-extrusion printing

The non-contact and mask-free co-extrusion process allows the printing of very narrow (<30 μm) and tall front-side grid fingers with a height of about 20 μm. Using these fingers, a short-circuit current and efficiency improvement compared to stencil and screen-printing have been demonstrated as shown below. The co-extrusion print system can align the printed pattern within less than ± 15 μm to selective emitter structures.

2.3.1. Print process

When using highly loaded, viscous metal pastes, such as those required for front side metallization in solar cells, it is challenging to use conventional dispense needles to achieve micron-scale features because of the high operating pressures required and resulting slow speeds in a production environment. Also a clogging of the nozzles is more likely to occur with this approach.

Leveraging the concept of hydrodynamic flow focusing [9], we have developed a single-pass, high-speed co-extrusion printhead technology for solar cell metallization that consists of a modular, non-bonded fluidic stack of nozzles. The co-extrusion printhead consists of a multi-layered nozzle assembly clamped between two sealing plate structures. A manifold plate distributes and splits two extrusion materials: a silver gridline paste and a sacrificial paste for shaping the silver gridlines into high aspect ratio features. The

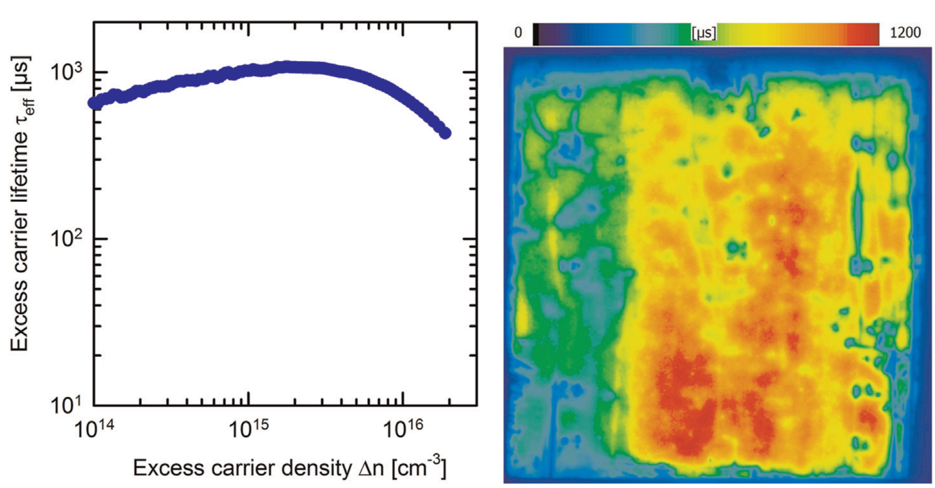

Fig. 1. QSSPC measurement curve (left) and calibrated PL lifetime map at 0.35 suns (right).