Solar Energy Materials & Solar Cells 157 (2016) 550–557

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

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

Flexographic printing – towards an advanced front side metallization approach with high throughput and low silver consumption

A. Lorenz [a,*], C. Gredy [a], S. Beyer [b], Y. Yao [c], P. Papet [c], J. Ufheil [b], A. Senne [d], H. Reinecke [e], F. Clement [a]

[a] Fraunhofer Institute for Solar Energy Systems (ISE), Heidenhofstrasse 2, 79110 Freiburg, Germany
[b] Somont GmbH, Im Brunnenfeld 8, 79224 Umkirch, Germany
[c] Meyer Burger AG, Schorenstrasse 39, CH-3645 Gwatt, Switzerland
[d] ContiTech Elastomer-Beschichtungen GmbH, Breslauer Str. 14, 7154 Northeim, Germany
[e] Albert-Ludwigs-Universität, Institut für Mikrosystemtechnik, Georges-Köhler-Allee 101, 79110 Freiburg, Germany

ARTICLE INFO

Article history:
Received 26 April 2016
Received in revised form
7 July 2016
Accepted 18 July 2016

Keywords:
Rotational printing technology
Flexographic printing
SmartWire Connection Technology
Multi-wire interconnection
Busbarless solar cells

ABSTRACT

Rotational flexographic printing technology is a highly promising approach to increase the productivity of the cost-intensive solar cell metallization process. The ability to realize narrow contact fingers with very low silver consumption makes this technology particularly attractive for the front side metallization of busbarless solar cells in combination with multi-wire interconnection like Meyer Burger's SmartWire Connection Technology (SWCT). Within this work, we investigate the feasibility of this approach on solar cells with 156 mm edge length. Two types of silver inks are prepared and evaluated with focus on optical and electrical properties of the printed front side grid. Both inks achieve sufficient lateral finger resistances below 20 Ω/cm. A low specific contact resistance of $\rho_{c,95\%}=3.0\pm0.6$ m Ω cm^2 is obtained with ink A. Using flexographic printing, Aluminum back surface field Czrochalski-grown Silicon busbarless solar cells with a maximum conversion efficiency of $\eta=19.4\%$ ($\eta_{\varnothing}=19.0\%$) are fabricated and interconnected to a mini-module. The mini-module obtains an aperture conversion efficiency of $\eta=15.8\%$. The origin of the cell-to-module (CTM) losses are examined in detail. It is shown that a certain part of the CTM-losses originates from the characteristics of the used Grid^{TOUCH} I–V-measurement device. Further sources of possible CTM losses are investigated using electroluminescence measurement (EL) and discussed in detail.

1. Introduction

To date, screen printing is the common technique for solar cell front and rear side metallization. However, this technology has some drawbacks – namely the limitation of throughput and the incapability to print very narrow lines with low silver consumption. A variety of alternative printing technologies like aerosol printing [1,2], inkjet [3,4], fine line screen printing [5,6], gravure [7] and others have been deeply investigated to overcome these drawbacks. Yet, an alternative technology can only prevail if it combines several requirements like high productivity, easy handling, high reliability and the possibility to use commercially available consumables (inks, printing forms etc.). Rotational flexographic printing is a very promising technology which meets these challenging demands. This printing technology is widely used in graphic arts printing on substrates like cardboard, paper or foil. Such printing machines can realize a printing speed of up to 800 m/min. on web based materials. However, this throughput can not be realized for non-continous printing on Si wafers. A single metallization line using rotational printing is expected to enable a throughput of 3000–5000 wafers/h which would be considerably higher than modern screen printing lines with approx. 2000 wafers/h. Fig. 1 illustrates the working principle of a flexographic printing unit for solar cell metallization.

A flexible relief printing plate is used as image carrier. Compressible foam tape is applied below the printing plate to support a homogeneous ink transfer. Low-viscous ink is transferred from the ink chamber onto the so-called anilox roll, a steel cylinder with a finely textured chromium or ceramic surface. Excessive ink is removed by a doctor blade before the anilox roller wets the elevated areas of the printing plate with a uniform layer thickness and directly prints the elevated printing image on the substrate. The flexible printing plate and the relatively low printing pressure enable a homogeneous and precise printing quality even on very rough substrates like textured silicon wafers.

Flexographic printing, also known as flexography or flexo, has

* Corresponding author.
E-mail address: andreas.lorenz@ise.fraunhofer.de (A. Lorenz).

http://dx.doi.org/10.1016/j.solmat.2016.07.025
0927-0248/

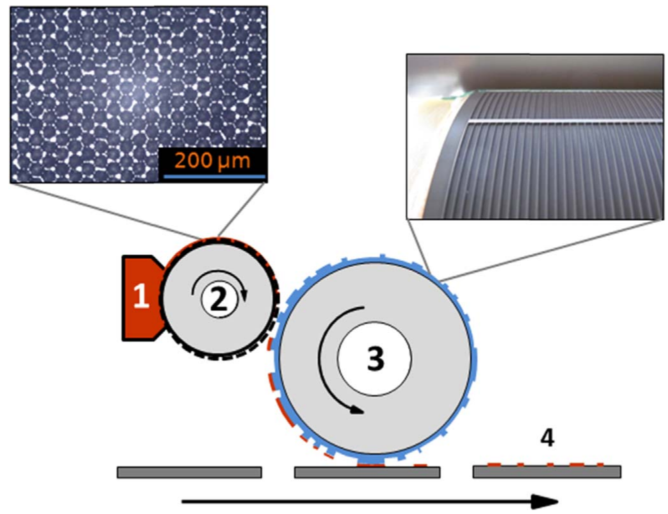

Fig. 1. Schematic drawing of a flexographic printing platform for silicon solar cells: From the ink reservoir (1), a defined amount of ink is transferred by the anilox roll (2) onto fine finger elements on the printing plate (3) and the silicon wafer (4).

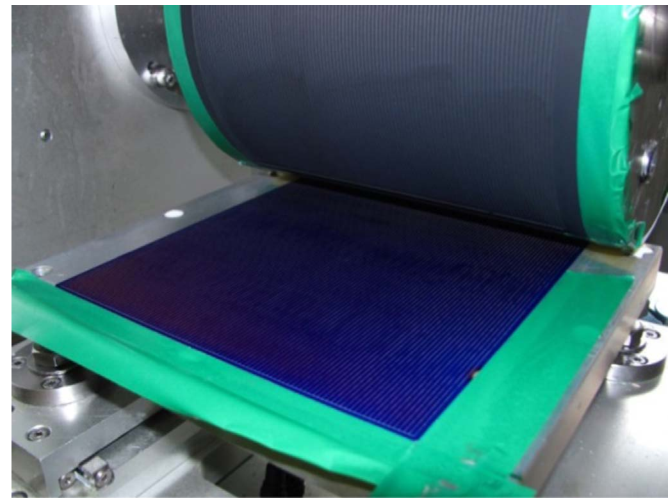

Fig. 2. Flexographic printing platform used for the experiment.

already proven its ability to print ultrafine conductive structures in many printed electronics applications like micro-scale conductive networks [8,9], roll-to-roll polymer solar cell modules [10], cathode layers for batteries [11] or conductive lines [12]. Feasibility studies using flexography on small-sized solar cell samples have demonstrated the potential of this technology to realize ultrafine contact fingers [13–15]. Conversion efficiencies up to $\eta = 18.8\%$ have been demonstrated for flexo-printed silicon solar cells using a seed and plate approach [16].

The interconnection of conventional H-pattern solar cells by stringing the cells with soldered ribbons on printed busbars causes significant electrical losses which limit the power output of the module. An innovative approach to overcome this drawback is the interconnection of busbarless solar cells by wire-bonding of multiple thin wires on the front side grid. Meyer Burger's Smart Wire Connection Technology (SWCT) is a very promising approach to realize this concept on an industrial base [17]. Busbarless solar cells with a front side grid consisting only of contact fingers are interconnected by 15–38 round copper wires. Typically, 18 wires with a diameter of $d_{wire} = 200\ \mu m$ are used for interconnection. The wires are coated with a low-melting alloy including 50% Indium [17]. The amount and thickness of the wires can be customized depending on the properties of the solar cell front side metallization. The wires are embedded in a PET foil, the so-called foil-wire electrode (FWE). The FWE is laminated with a certain pressure and temperature directly onto the front and rear side of the solar cells. SWCT offers the potential to reduce costs and raise module efficiency considerably due to several benefits. Ohmic power losses of the front side grid can be reduced due to significantly smaller finger segment lengths in between the wires. Silver consumption is considerably smaller due to the lack of printed busbars and the possibility to print smaller fingers. Light coupling into the module is increased due to a better back-reflection behavior of the round-shaped wires. The passivation quality of the rear side is increased as no silver solder pads are needed. Finally, the impact of cell breakage is considerably smaller due to multiple current collection pathways [17]. A detailed feasibility study has shown that flexographic printing is a highly interesting for the front side metallization of busbarless solar cells [18]. Within this work, we demonstrate the first busbarless solar cells with flexo-printed front side metallization and a fully functional mini-module with SWCT interconnection.

2. Experiment

2.1. Wafer material

The experiment is carried out using industrially pre-produced Czrochalski-grown Silicon (Cz-Si) p-type solar cells up to anti-reflection coating (precursors) with an edge length of 156 mm. The precursors have a p-type base resistivity of approx. $\rho_b \approx 2.8$–$3.3\ \Omega$ cm and a n-type phosphorous doped emitter with a sheet resistance of $R_{sh} \approx 85$–$90\ \Omega$/sq. The front side is textured by alkaline wet chemical etching and coated with SiN_x anti-reflection coating (ARC) by plasma-enhanced chemical vapor deposition (PECVD). The rear side of the cells is metallized with screen printed aluminum paste to form the back surface field (Al BSF) after contact firing.

2.2. Printing platform

A roll-to-flat flexographic printing platform *Nissha Angstromer S15* is used to apply the front side metallization of the solar cells (Fig. 2). This machine has a vacuum substrate holder to fix the wafer during the printing process. The position of the vacuum substrate holder perpendicular to the axis of the printing cylinder (*z*-position) is adjusted by a micrometer spindle. A tri-helical engraved anilox roll with a screening of 119 lines/cm and a nominal dip volume of $V_D = 7.2\ cm^3/m^2$ is used to transfer a constant amount of silver ink on the printing plate. The ink is applied by a pipette directly on the anilox roller. A steel doctor blade removes the excessive ink from the anilox roll.

A double printing step with an intermediate drying step using an industrial heating blower is applied on the front side of the precursors. The register accuracy between the two printing steps on the used machine is estimated with approx. $\pm 5\ \mu m$ as the wafer is constantly fixed by vacuum during the whole procedure. For an industrial application of this process, it would thus be necessary to realize a serial arrangement of two printing units with a register accuracy of $\pm 10\ \mu m$ or better. In contrary to a previous experiment [19], several process optimizations are applied. Instead of a hard substructure under the printing plate, a stack of soft foam tapes is used. It is anticipated that this softer substructure helps to reduce the deformation of the finger elements on the plate under pressure and thus prevents excessive spreading of the ink. Secondly, an new ink formulation with a higher viscosity is used. Thirdly, an optimized three-dimensional shape of the contact fingers on the laser-engraved elastomeric plate is realized. Finally,