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Industrial PERL-type solar cells exceeding 19% with screen-printed contacts and homogeneous emitter

Matthieu Moors*[,1], Kasper Baert, Tom Caremans, Filip Duerinckx, Antonio Cacciato, Jozef Szlufcik

Photovoltech N.V., Industrial Area West Grijpen, Grijpenlaan 18, B-3300 Tienen, Belgium

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ABSTRACT

Aiming at the development of a cost-effective and industrially up-scalable process for the production of p-Si PERL-type solar cells, this work focuses on the selection and the development of an optimal rear-contacting method of screen-printed aluminum back electrodes through AlO_x-based rear passivation stacks. Laser-Fired Contacts are first optimized by developing dedicated characterization protocols to define an optimal laser process. Laser parameters are systematically varied (e.g. pulse energy, power density, focus, and contact pitch) and their effect on the contacts quality is analyzed. Besides, a new contacting method, called Extended-Laser-Ablation (ELA), is presented, allowing even higher efficiencies to be attained thanks to better quality of local back-surface fields. Both contacting routes are then implemented and compared in the PERL pilot production process flow to investigate their effects on cells performances. Top efficiencies of 19.13% (AlO_x/SiN_x) and 19.5% ($SiO_2/AlO_x/SiN_x$) are reached when the ELA process is used on monocrystalline Cz Si, using a close-to-standard process (75 Ω/sq homogeneous emitter, screen-printed contacts, standard cleaning procedure), without any final forming gas annealing step required.

1. Introduction

Developed at the laboratory scale at the end of the last century, Passivated Emitter, Rear Locally diffused solar cells (PERL) are still holding the 25% world efficiency record on mono-crystalline silicon when using a single junction [1–3]. Almost fifteen years later, the industrial production of this elegant cell design remains one of the most interesting challenges for the photovoltaic industry. Besides the immediate cost issue arising from an increased number of production steps, and from novel type of equipment, the development of high-throughput, stable and controlled processes remains indeed challenging. Regarding the metallization of the passivated rear side, several strategies have been proposed, often based on the use of lasers [4–6]. This technique can indeed be considered as the most cost-effective way to replace expensive photo-lithography-based processes (used, for example, to open dielectric layers locally). Among those contacting strategies, Laser-Fired Contacts (LFC) still look as one of the most promising options [5], although this process still faces some important issues for industrial implementation. Indeed, especially when working with screen-printed aluminum layers, it is difficult to obtain thick and continuous Local Back Surface Fields (L-BSF) around the metal contacts [7]. Moreover, a final forming gas anneal step (FGA) is often necessary to cure the laser-induced damage done to the substrate and recover high V_{oc} and fill-factors from laser-treated cells [8].

The first part of the current work is thus focused on the development of a production-worthy LFC contacting method. Fully screen-printed PERL-type cells, AlO_x-based rear passivation and LFC formed in a single laser pulse are exclusively studied. First, the LFC process window is defined by measuring the resistance of individual contacts created using different laser pulse energy. Then, further optimization is achieved using photoluminescence, electroluminescence and scanning electron microscopy. The optimized process is finally implemented in our pilot production line to study its impact at cell level.

In the second part of this paper, a new rear contacting technique is presented, called Extended Laser Ablation (ELA), which aims at obtaining higher quality Local Back Surface Fields around the contacts. The basic principles of the method will be described and results at cell level will be presented in comparison with LFC samples. Both methods have been developed while globally keeping the target of preserving the short-term industrial up-scalability of the process. Therefore, a standard design is conserved on the front side (homogeneous emitter–75 Ω/sq–SiN_x ARC–screen-printed contacts), expensive cleaning steps are avoided (only the standard HF/HCl before phosphorus diffusion is kept), thin dielectric layers are used (~100 nm stack) and final Forming Gas Anneal treatments

* Corresponding author. Tel.: +32 16 804 462; fax: +32 16 805 914.
E-mail address: matthieu.moors@photovoltech.be (M. Moors).
[1] http://www.photovoltech.be

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(FGA, often needed in LFC-based process flows to heal laser damage and recover high V_{oc} values [8]) are deliberately suppressed.

2. Experimental

All the present work is executed on Cz monocrystalline silicon (p-type, 2 Ω cm, 6″ squared wafers, 180 μm thick), following an industrial process flow (acidic or alkaline texturing, single-side polishing, 75 Ω/sq homogeneous emitter, wet-edge isolation (WEI), SiN_x ARC deposited by PE-CVD). AlO_x and SiN_x are then consecutively deposited on the rear side, directly after the wet-edge isolation step. If a $SiO_2/AlO_x/SiN_x$ rear passivation design is studied, a thin dry oxide layer is grown after WEI in a classical tube furnace, immediately followed by AlO_x and SiN_x depositions. High-throughput deposition tools are used for this purpose (Roth & Rau PE-CVD and Levitech Spatial ALD). Screen-printing is used for both front and rear metallization (commercial Ag and Al pastes), followed by a standard co-firing step in an IR belt furnace. A full Al layer is printed on the rear, without Ag tabs. Concerning the Laser-Fired Contacts experiments, LFC are processed as the final step (no FGA). A disk laser (60 W, ~1 μs pulse length) is used for laser processes ($\lambda = 1032$ nm). A matrix of dots with a pitch of 0.4 mm is used as rear contact pattern for every cell. An in-house developed 4-point-probe measurement procedure is achieved to measure individual contact resistances. Commercial photo/electro-luminescence (BT-imaging) and scanning electron microscopy/EDS (JEOL JSM-6010LA) tools are used for finer process optimization. Solar cells are finally tested using a Berger solar simulator under standard illumination conditions (AM 1.5 G, 1000 W/m^2, 25 °C).

3. Results and discussion

3.1. LFC optimization

To quantitatively estimate and optimize the resistance of LFC (R_{LFC}), a matrix of isolated Al squares is printed on the rear side of a PERL-like cell while fully metallizing the front side with Al (Fig. 1a). A specially designed screen is used, presenting a thin emulsion-on-mesh that allows for perfectly flat squares to be obtained, which present the same thickness as the full Al layer printed on our PERL-like cells. LFC are then processed on the full wafer rear side, aiming at getting four contacts per square. The electrical resistance of these individual patterned squares is then measured across the wafer using a four-point (micro-)probes system. The resistance of individual LFC is finally extracted from the measurements and the mean value is plotted against the laser pulse energy (Fig. 1b). Neglecting the contribution of the fully metallized front side, one can assume two contributions to the LFC resistance: $R_{LFC} = R_c + R_{sp}$, R_c being the contact resistance and R_{sp} being the base spreading resistance. An ideal contact would then show $R_{LFC} = R_{sp}$ [9]. This spreading resistance limit can thus be looked at as a target value for choosing the most appropriate laser parameters from a contact resistance point of view. As presented on Fig. 1b, using high energy laser pulses provided close-to-perfect contact resistances.

Transferring the results of this study to a full cell process allowed us to obtain fill-factors above 78%, using a single high energy pulse per contact and decreasing the process time under 5 s per cell. However, using high energy pulses, although leading to very low contact resistivities, induces considerable damage to the Si wafer, leading to important drops in V_{oc}, by up to 15 mV. As we chose to avoid any final FGA treatment (that would eventually recover those parameters [8]), a compromise between low contact resistance and minimal laser damage had to be found. This has been achieved using electro- and photoluminescence (EL/PL) as fast feedback techniques to fine-tune the process.

Solar cells are first processed up to the LFC step. Different laser processes are then carried out on seven separated zones of the same cell, which can be simultaneously inspected using PL in order to estimate the amount of laser-induced damage. Subsequently, the electro-luminescence mode of the tool allows for series resistance maps to be extracted, revealing optimal contacts locations. A best set of laser parameters can then be easily selected from this analysis by seeking for the processed zone which appears the brightest in PL and the darkest on the R_s map (see Fig. 2a and b). For example, on the left-hand side of the presented sample, a higher lifetime is obtained but the series resistance increases accordingly. The best compromise on this wafer is thus chosen on the fourth zone. Individual LFC are finally inspected in the Scanning Electron Microscope and chemically analyzed by EDX mapping. Contact diameter (measured at the Si wafer level) and depth stand in the range of 40 μm and 20 μm, respectively. Fig. 2c and d present an example of two contacts processed with different laser parameters. The first one shows a homogeneous morphology while the second one clearly reveals inappropriate laser settings leading to non-homogeneous contacts (and much lower fill factors).

The optimized LFC parameters were finally implemented in our pilot production line leading to the results presented in Table 1. Given the absence of any FGA treatment, those results are encouraging towards the industrial production of 19% efficiency LFC-processed PERL-like solar cells in the near future.

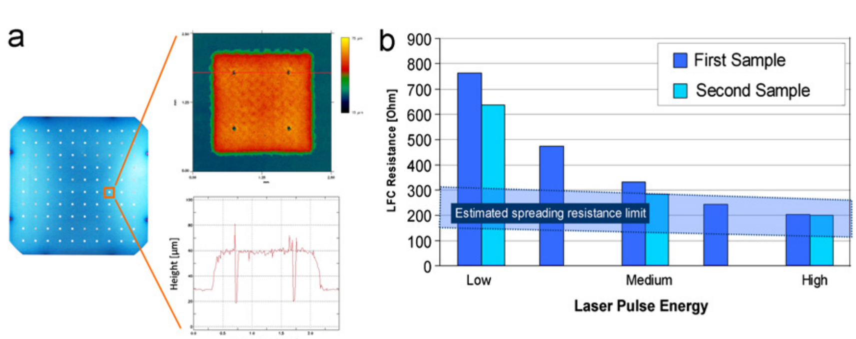

Fig. 1. (a) Profilometry micrograph and related profile showing one of the 1.8 × 1.8 mm^2 squares of Al printed on an AlO_x/SiN_x-passivated Si wafer in which four LFC have been lasered. (b) Measured individual LFC resistances (R_{LFC}) plotted against the laser pulse energy. The light blue area highlights the calculated spreading resistance R_{sp}, based on either the internal (at the Si wafer level, ranging from 35 to 40 μm depending on laser pulse energy) or the external diameter (at the Al paste level, ranging from 70 to 80 μm respectively) of the contact. At the limit of negligible contact resistance, $R_{LFC} = R_{sp}$ [9]. This experiment has been reproduced on two samples of identical resistivity. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)