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STABLE COPPER PLATED METALLIZATION ON SHJ SOLAR CELLS & INVESTIGATION OF SELECTIVE Al/AlO$_x$ LASER PATTERNING

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ABSTRACT: Copper plating metallization is growing in importance to replace silver and to enable growth of photovoltaic to terawatt-scale. Besides better performance of the plated Cu contacts on solar cells, the processing needs to be less complex and more cost effective. The „NOBLE“ metallization responds to cost savings for bifacial silicon heterojunction solar cells. This study shows that the processing with inkjet-printing for patterning of the top Al masking layer is yet mature enough for first tests on industrial pilot. Efficiencies comparable to the Ag screen-printed reference on the same precursors grade are reached. To even improve the patterning throughput a selective laser ablation patterning of the Al/AlO$_x$ layer is further investigated. There, laser-induced damaging is avoided by choosing adapted laser settings and first large area SHJ solar cells are manufactured with this method yielding an encouraging 21.4% efficiency.

Keywords: Silicon Heterojunction Solar Cell, Metallization, Copper Electroplating, Laser Processing, Inkjet-printing, Cost reduction

1 INTRODUCTION

Next generation high efficiency silicon solar cells rely on passivating contacts such as the silicon heterojunction (SHJ) technology [1]. Improvement of the technology enabled to reach record efficiencies above 25% on large area cells in the past years [2–5]. To maintain the exponential growth of photovoltaic (PV) towards terawatt (TW) scale, material supply is an important concern [6–8]. Especially silver supply will soon become a bottleneck and is already causing 10% of the costs for a typical solar module. The metal contacts on bifacial SHJ solar cells are manufactured on both-sides by screen-printing low-temperature silver paste. This causes even higher silver consumption and costs for this technology. Unfortunately, the silver saving smart wire technology (SWCT) suitable for interconnection and module integration of SHJ solar cells will be no longer available to all manufacturers [9].

Thus, intrinsic low-temperature copper plating metallization featuring high performance is growing in importance as alternative for SHJ solar cells [10]. In different parts of the globe an industrially viable electroplating route using a sacrificial organic resist-mask (on a PVD metal-seed deposited on the transparent conductive oxide (TCO)) is under development and outstanding efficiencies around 25% were reported [2, 11].

Our resist-free native oxide barrier layer for selective electroplating („NOBLE“) metallization aims at reducing the plating process complexity and processing cost [12], making this route attractive for industrial implementation. Instead of using an organic mask for electroplating, the „NOBLE“ metallization implements a conductive self-passivated Al layer as detailed below. The first proof-of-concept was achieved on lab-scale SHJ solar cells [13] before being transferred on large area recently yielding up to 22.7% similar to the screen-printed reference on the same SHJ precursors [14].

This study shows that the „NOBLE“ metallization is already running stabile on large area medium grade SHJ precursors when using the optimized NaOH$_{aq}$ inkjet-printing patterning of the Al layer [15]. In addition, a selective laser ablation patterning route of the Al/AlO$_x$ layer is investigated to facilitate the processing sequence, improve the patterning resolution and increase the throughput even more.

2 APPROACH

Our „NOBLE“ metallization consists in using a conductive self-passivated Al layer as plating mask while providing homogeneous current distribution on the wafer surface during simultaneous bifacial electroplating. The complete process is depicted in **Figure 1**.

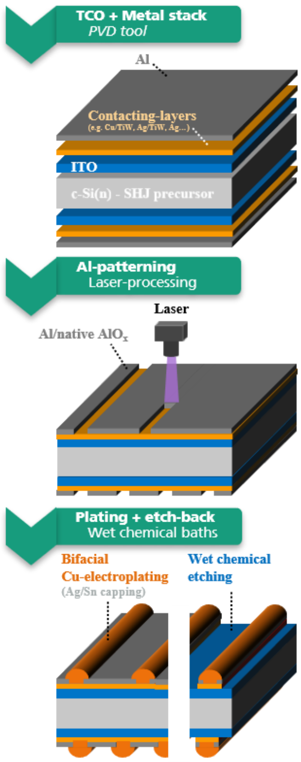

Figure 1: Schematic sequence of the „NOBLE“ metallization with laser patterning

Following the physically vapor deposition (PVD) of the TCO layer, an additional thin PVD metal stack (with Al on top) is deposited on full area. At the grid position, Al is locally removed from the underlying PVD-Cu or -Ag layer. This patterning is was until now performed by $NaOH_{aq}$ inkjet-printing but a new method using selective laser ablation of the Al/AlO_x layer is being developed as shown in the schematic. The exposed PVD-Cu or -Ag layer act as seed-layer for selective Cu electrodeposition. Finally, the PVD metal stack is etched back in non-grid positions.

The „NOBLE" plated Cu contacts on SHJ solar cells achieved superior electrical and mechanical performance compared to typical Ag screen-printed ones as shown in **Table** 1. It is noteworthy that by reducing the finger width, contact resistivities ρ_c below 1 mΩ·cm² are required to avoid impacting the series resistance of the solar cell. This requirement is well met with the „NOBLE" metallization.

First part of this work consists in a demonstration of a first pilot run with a higher amount of SHJ solar cells with the optimized $NaOH_{aq}$ inkjet-printing patterning of the Al. Therefore, industrial SHJ precursor (M2) with ITO were covered on both-sides by different PVD metal stacks (e.g. TiW/Ag, Ag…) with a 50 nm thin Al layer on top. After complete „NOBLE" processing, the I-V curves were measured in a sun-simulator.

Table 1: Comparison of the metal finger characteristics on SHJ solar cells with ITO based on [12, 16]

Process	Width [µm]	ρ_L [µΩ·cm]	ρ_c [mΩ·cm²]	Peel-force [N/mm]
Plated Cu (NOBLE)	25-30	≈ 2	0.1 - 1	≥ 2
Screen-printed Ag	30-40	≥ 5	≥ 2	≤ 0.5

Secondly, a new patterning method is investigated using a femtosecond UV laser (at 343 nm) for selective ablation of the top Al layer on the SHJ precursors. The laser ablation is optimized for the respective layer stack and characterized by photoluminescence imaging (PL) at 1-sun. The thickness of the PVD metal stack (Cu_{500nm}/Al_{100nm} and Ag_{100nm}/Al_{50nm}) is varied to evaluate the laser-induced damage of the passivation on such SHJ solar cells (same batch as above). The complete „NOBLE" process is finally performed to produce the first large area SHJ solar cells using the selective laser patterning of Al.

3 RESULTS

3.1 Stabilized sequence with inkjet-printing patterning

The large area SHJ solar cells were metallized with the „NOBLE" approach using different PVD metal seed-layers below the Al (e.g. TiW/Ag, Ag…). The I-V performances presented in **Figure 2** highlight the reproducibility of the cell efficiency around 22.6%, which is very close to the Ag screen-printed reference. The inkjet-printing enables to keep the passivation quality of the SHJ solar cells at the highest level above 735 mV. Last improvements of the inkjet-printing process are still necessary to benefit fully from the narrow plated contacts and to reach higher fill-factor FF and current density j_{sc} above 38.5 mA/cm² on this precursors type (no additional ARC, just ITO).

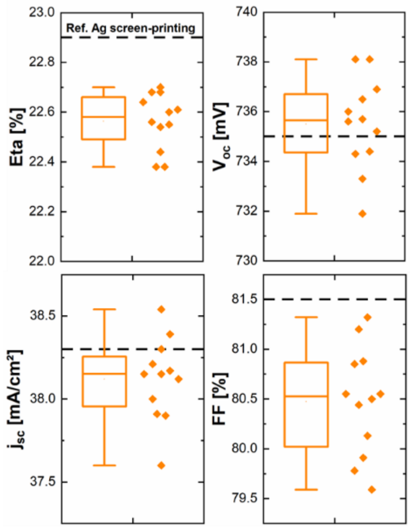

Figure 2: Reproducible I-V characteristics reached on 12 large area SHJ solar cells metallized with the „NOBLE" approach (inkjet patterning) compared to the best screen-printed reference (black dashed line) on the same industrial SHJ precursor material

These promising I-V results confirm that the „NOBLE" metallization with inkjet-printing patterning yields stable results which is required to soon highlight the full potential of plating on high quality materials.

3.2 Patterning by selective laser ablation of Al/AlO_x

First developments of the new selective laser ablation of the thin Al layer show two possible ways to avoid damaging the SHJ cell passivation. One is using a thicker underlying PVD metal layer (contacting layer to plate) as buffer during lasering with high laser pulse energy to locally remove the Al layer with a single laser pulse. The impact of pulse energy on the damage is shown by photoluminescence imaging in **Figure** 3 **(Left)**. Except for the highest pulse energies (4.3 and 4.7 µJ), this buffer layer enables to prevent laser-induced passivation damaging. Furthermore, the Al layer opening seems to be compatible with selective copper electroplating.

The second way is to use low laser pulse energy but multiple laser pulses on the same spot to remove the Al layer bit by bit. As illustrated in **Figure 3 (Right)**, the process window that allows avoiding laser-induced damaging of the passivation is smaller. The Al opening seems less efficient but selective copper plating also worked with this approach for defined parameters and an encouraging contact resistivity ρ_c down to 1.6 ± 0.3 mΩ·cm² was measured.

Further investigations will refine the damage free process window and explain the mechanismus of degradation resulting from ablation.

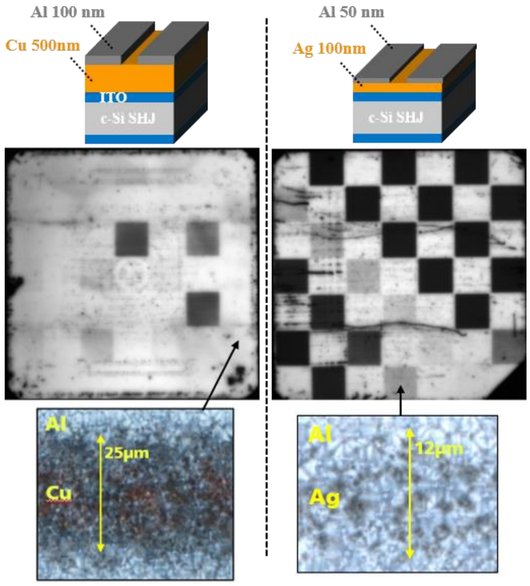

Figure 3: Photo-luminescence (PL) imaging at 1-sun and respective microscopy pictures after femtosecond pulse laser ablation (at 343 nm) of the Al layer depending on the PVD metal stack thickness. (Left) High pulse energies between 2.2 and 4.7 µJ. (Right) Low pulse energies between 0.2 and 0.7 µJ with pulse repetitions per laser dot from 1 to 35 times

3.3 SHJ solar cells manufactured by laser patterning

This early development of the selective laser ablation patterning of the Al/AlO_x masking layer enabled to manufacture first large area SHJ solar cells with the modified „NOBLE" route. The high laser pulse energy with the adequate thicker "buffer layer" was prioritized. The best laser settings were used to metallize the front-side grid in the Al layer. After full processing of the front-side, the rear-side of the SHJ solar cell was metallized by Ag-paste screen-printing. The I-V characteristics reported in **Table** 2 are quite promising as proof-of-concept and not too far from the reference with inkjet patterning. The limited efficiency is explained by a loss of about 10 mV in V_{oc} probably due to passivation damages with such an early stage laser process. The FF is not as high as expected due to finger interruptions resulting from inhomogeneities in the PVD Al layer thickness and/or the focusing of the laser beam. It can be noticed that the pFF of the SHJ cell also seems to be affected. However, a gain in j_{sc} is achieved thanks to the narrower contacts ≤ 25 µm enabled by the laser patterning.

Table 2: I-V characteristics of the best large area SHJ solar cells after „NOBLE" metallization with laser ablation or $NaOH_{aq}$ inkjet-printing patterning of the Al top layer

Patterning process	Eta [%]	V_{oc} [mV]	j_{sc} [mA·cm^{-2}]	FF [%]	pFF [%]
Laser	21.4	726.8	38.6	76.3	83.4
Inkjet-p.	22.7	735.7	38.3	80.5	84.4

The low pulse energy and pulse overlaps laser patterning approach also enabled to manufacture first large area SHJ solar cells with the most promising laser settings. Despite of the non-optimized opening of the Al layer, selective plating was successful and narrow Cu contacts ≤ 25 µm wide were produced after complete processing as shown in **Figure 4**. The PL characterization of a quarter of the solar cell after complete sequence revealed an encouragingly low damage of the passivation as observed in **Figure 4.**

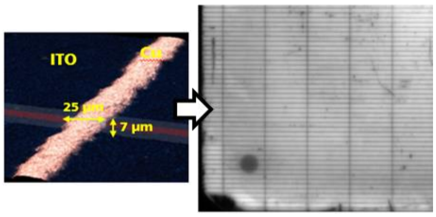

Figure 4: SHJ solar cell after metallization with laser patterning (low pulse energy and pulse repetitions per laser dot). (Left) Microscopic picture of a narrow plated Cu finger. (Right) Enlarged PL picture at 1-sun from the grid-side

4 CONCLUSION

This work shows SHJ solar cells fabricated with an optimized plating process sequence resulting in stabilized I-V performances of 22.6% efficiency comparable to the screen-printed reference. The so-called „NOBLE" approach with inkjet patterning is considered to be mature enough to be tested on industrial pilot line.

Furthermore, a new selective laser ablation process for the top Al layer is demonstrated on textured SHJ solar cells. An encouraging efficiency of 21.4% in this first experiment confirm the potential of the fast contactless patterning method. Further work should therefore enable a fast improvement of this laser-based method for industrial implementation of our resist-free copper metallization.

ACKNOWLEDGEMENTS

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