Direct Contact Electroplating Sequence Without Initial Seed Layer for Bifacial TOPCon Solar Cell Metallization

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Abstract—The metallization of bifacial tunneling oxide and passivating contacts (TOPCon) solar cells without initial metal seed layer by electroplating of Ni/Cu/Ag is demonstrated. The presented approach allows a lead-free metallization with narrow contact geometries and low contact resistivity. A metal plate provides electrical contact to the silicon via micrometer size laser contact openings and allows electroplating of bifacial TOPCon solar cells using industrial type inline plating tools without the need of a previously applied seed layer. Challenges such as direct contacting of silicon and dissolution of contacts are identified, and potential solutions are discussed. An optimized process sequence is developed and with this approach a solar cell efficiency of 22.5% is demonstrated on industrial bifacial TOPCon solar cells reaching the same level as the screen-printed reference solar cells.

Index Terms—Forward bias plating (FBP), light induced plating (LIP), passivating contacts, silicon solar cells, tunneling oxide and passivating contacts (TOPCon).

I. INTRODUCTION

Solar cells featuring carrier selective contacts such as tunneling oxide and passivating contacts (TOPCon) consisting of a thin oxide layer and a highly doped poly-Si, which significantly reduces contact recombination have attracted an increased interest lately. Their potential was already shown on an n-type both sided contacts lab cell by Richter et al. [1] with 25.8% efficiency [2] and single-sided contacted IBC lab cell by Haase et al. [3] with 26.1% both on 4 cm² sample size. The industrial implementation referred as i-TOPCon featuring carrier-selective contacts (TOPCon) solar cells without initial metal seed layer by Richter et al. [1] might be suitable for bifacial TOPCon solar cells. This method requires a silicon selective surface activation of the silicon interface. Simultaneous bifacial electroplating requires a sufficient lateral conductivity of a seed layer along the wafer surface [11], [12]. In this article, we present a new plating process sequence for bifacial TOPCon solar cells omitting the necessity of a conductive seed layer by contacting directly the silicon within laser contact openings. This approach was introduced by Gensowski et al. [13] as direct contact plating. It enables successive single-sided electroplating on each side of a bifacial solar cell. State-of-the-art single sided plating tools such as inline plating tools were used in this work to demonstrate direct contact plating for bifacial TOPCon solar cells.

II. EXPERIMENTAL

A. Approach and Plating Conditions

The direct contact plating process sequence is displayed in Fig. 1. Prior to the plating process, the dielectric antireflection coating on both sides of the solar cell is locally removed by laser ablation using a UV ps-laser corresponding to the desired grid

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Fig. 1. Direct contact electroplating sequence including HF pretreatment and Ni/Cu/Ag plating with an optional annealing for bifacial TOPCon solar cells. The mentioned side refers to the side where the deposition takes place. The contacting of the solar cell is performed by a temporary metal contact consisting of a metal plate placed on surface of the solar cell. The side contacting the laser contact openings is coated with a Ni layer.

design. According to the intended orientation of the solar cell toward the sun, the n-type doped side is defined as rear side, whereas the p-type doped side is referred to as front side in this work. The process sequence for plating on the rear side consists of a single-sided low concentrated HF pretreatment in order to remove any oxide layer within the laser contact opening (LCO). Subsequently, Ni and Cu plating is performed by light induced plating (LIP) by immersing the laser patterned solar cell precursor single-sided in the plating electrolyte while being illuminated by LEDs positioned in the electrolyte. On the nonimmersed (dry) side of the wafer the LCOs are temporarily contacted by a metal plate as visible in Fig. 1 (zoomed circle) with a constant current and a voltage limit of 20 V. The metal plate features a Ni coating on the side facing the solar cell. For this plate a small margin (∼1 cm) on each side is kept to avoid wetting of the temporary metal contact by the electrolyte, which would lead to preferential deposition onto the metal plate instead of the solar cell. In order to improve the contacting, the temporary metal contact can be pressed onto the wafer. The plated metal stack is finished with a single-side chemical Ag capping carried out by electrolysis (immersion) plating. Subsequently, the solar cell is flipped and almost the same process sequence for depositing Ni and Cu is applied. However, this time the temporary metal contact is contacting the already plated grid on the rear side and no light is required for plating as the pn-junction is under forward bias (forward bias plating (FBP) [14]). The front side is capped in the electrolysis Ag bath as well. The selected electrolytes for Ni, Cu, and Ag plating are presented in Table I. All plating processes are performed in lab-type versions of the inline plating tool “InCellPlate” of the company Rena Technologies GmbH. All plating steps are single-side processes apart from the annealing step. The light intensity of the LEDs of the inline tools can be adjusted so that the current generated by the solar cells can be controlled. This means that for an external current that is lower/higher than the generated current of the solar cell, the external / solar cell current is limiting the accessible current for the plating deposition. In this work, the light intensity was kept constant at a level so that the current generated by the solar cell is higher than the external current. The plated solar cells were annealed after plating in order to reduce the contact resistance and increase the contact adhesion [15], e.g., by an offline laser based rapid thermal processing oven [16].

The contacting of the solar cell to perform the electroplating process is an essential aspect for the presented process sequence. Especially, the homogeneous contacting of a textured silicon surface is challenging as outlined in the sketch in Fig. 1 (zoomed circle). As the contacted area is unknown a precise contact resistance is not accessible. However, a way of characterizing
contacting. Lennon et al. [18] = × stack. The rear side features an n-type TOPCon layer exceeding 100 nm coated with SiNx. Three metallization designs were selected as displayed in Fig. 3. On both sides of the bifacial plated solar cells laser patterning with 9 busbars and 96 fingers were performed with an UV ps-laser followed by a firing in an industrial conveyor belt furnace. The precursors were then plated on both sides according to the plating sequence presented in Section (II. A). Screen printed cells were used as reference with identical grid design. The IV measurements were performed at a flash IV tester (cetisPV-Celltest3 / HALM). A GridTouch contacting [18] unit was used due to a limitation of the maximum number of contacting rails in the IV tester. In addition, hybrid TOPCon solar cells were produced with screen-printed contacts on the rear side and plated contacts of the front side. This design was only used to characterize the plating results and effects.

B. Solar Cells

In this work, industrial bifacial n-type TOPCon solar cell precursors (158.75 × 158.75 mm²) after passivation and optimized for screen-printing metallization were selected as shown in Fig. 1. The textured front side consists of a p-type boron emitter passivated by an AlOx/SiNx stack. The rear side features an n-type TOPCon solar cell with a confocal laser microscope (LEXT OLS4000). More than 50 positions randomly distributed over the cell were measured for each side of the processed solar cells. The dimensions of the metal contacts were characterized using a confocal laser microscope (LEXT OLS4000). More than 50 positions randomly distributed over the cell were measured for each side of the processed solar cells, to get the general appearance of the fingers as well as the contact dimensions (height and width). For more extensive characterization of the contact properties, some additional samples were processed with the opposite process sequence as displayed in Fig. 1 by plating the front side first followed by the rear side. Contact resistivity
measurement of the plated contacts via transfer length method (TLM) [19] were performed as well as contact angle measurements on each side of the solar cell samples on an OCA 20 contact angle system (Dataphysics).

III. RESULTS AND DISCUSSION

A. IV Results

In Table II, the IV results of the solar cells are presented. The reference solar cells (bifacial Ag/AgAl screen printed TOPCon solar cells) of the same precursor batch achieved an efficiency of $\eta = 22.5\%$. With the presented direct contact plating sequence an identical efficiency of $\eta = 22.5\%$ was reached. The pseudofill-factor $pFF$ is similar for both metallization groups. The series resistance is identical for both solar cells resulting in a $FF$ of 81.9%. The lower open-circuit voltage $V_{oc}$ of the plated solar cell is compensated by a higher $J_{sc}$ ($+0.2$ mA/cm²) originating mainly from smaller contact widths resulting in the end in an identical efficiency. The limited number of solar cells processed, does not allow a statistical evaluation. The $V_{oc}$ of all samples is subject of sample to sample variation. It has to be noted that the grid design (finger and busbar number) was optimized for screen printed reference solar cells and not changed for the plated solar cells in order to simplify the comparison.

Additionally, the contact resistivity of the plated TOPCon solar cells was characterized by TLM measurements. The contact resistivity of plated Ni/Cu/Ag contacts on boron emitter and TOPCon surfaces was measured as $\rho_{c, \text{boron}} = (0.3 \pm 0.2)$ m$\Omega$cm$^2$ and $\rho_{c, \text{TOPCon}} = (0.4 \pm 0.4)$ m$\Omega$cm$^2$, respectively. The measured values are in the range of recently published contact resistivities [8]. The measured finger resistivity for the plated contacts is around $(1.79 \pm 0.2) \times 10^{-8}$ $\Omega$·m only slightly higher than the literature value for Cu $(1.72 \times 10^{-8}$ $\Omega$·m) [20].

B. Direct Contact Plating

In Table IV, the measured voltage (see Fig. 2) during plating for different contacted interfaces is shown depending on the plating current density. The voltage is a sum of several contributions such as the contacting, the solar cell and the parts inside the electrolyte. If silicon within the LCO is the contacted interface during plating, a voltage exceeding 20 V is required to distribute the current density of 2 A/dm² for Ni plating. As
this is abovementioned the adjusted voltage limit the target current density could not be reached. To improve the contacting of the interface between the temporary metal contact and the LCO, the temporary metal contact was gently pressed onto the wafer with a contact pressure of 122.6 $\times 10^{-3}$ N/cm². This led to a reduction of the required plating voltage for Ni (<5 V at 2 A/dm²) and Cu (10–15 V at 8 A/dm²) independently of which side of the TOPCon solar cells was plated first. As only the contact interface between the temporary metal contact and the LCO is modified the lowering of the plating voltage can be fully attributed to the improved contacting. Presumably the increased pressure increases the actual contact area to the textured silicon, as more pyramid tips come into contact with the applied metal plate as well as the contact area for every single pyramid is increased. The applied pressure was moderately small so that the wafer did not suffer any structural impact. According to the IV results and additional microscopy characterization of the surface after applying such a pressure no impact was observed. As a metal contact is applied onto the wafer, in an industrial approach it is thinkable that the contact pressure can be either generated by the weight of the metal contact itself or by adjustable springs applying pressure onto the metal contact. When flipped, the contacted interface counteracting the temporary metal plate consists of a plated Ni/Cu/Ag metal stack. Therefore, without the need of additional pressure, a plating voltage around 5 V was measured as the first Ni deposition takes place followed by a drop in voltage within seconds fluctuating around 2–3 V even for Cu plating where higher current densities (8 A/dm²) were used.

Plating of bifacial TOPCon solar cells requires higher plating voltages for contacting the silicon within the LCO. Nevertheless, inhomogeneity of the plated contacts due to inhomogeneous contacting could not be observed. The high voltage was found to originate mainly from the limited contacted area of the temporary metal contact. However, due to the limited contact area the high voltage might lead to side effects such as damage on the silicon surface due to small discharges (corona discharge [22]). Even though the contact pressure between the temporary metal contact and the LCO significantly reduced the plating voltage for Ni plating, Cu plating with a plating current density of 8 A/dm² still required around 10–15 V. A further increase of deposition rate and the plating current density for higher throughputs would lead to an increase in the required plating voltage. Although the homogeneity is not affected smaller contact cross sections (height and width) can be a consequence as the full plating current is not reached.

### C. Contact Modifications due to Electrolyte Wrap-Around

The presented plating sequence for bifacial TOPCon solar cells consists of plating the full Ni/Cu/Ag stack on one side of a solar cell followed by plating of the same metal stack on the opposite side. During the plating process–independently of which side is plated–a wrap-around of the electrolyte occurs, wetting the surface in a range of 5 mm wide area on the otherwise dry side close to the edge. The wetting results in an additional current path as displayed in Fig. 2 by the inner mesh ($I_2$). The origin of the edge wetting is most likely due to wetting properties along the rough wafer surface (texture/polished texture surface). Furthermore, contact angle measurements support that the general wettability properties of the dry surface play a major role. Moderate hydrophobic surfaces prevent electrolyte wrap around, which was usually experienced at Fraunhofer ISE for single-side plating of PERC solar cells with measured contact angles above 40°. The TOPCon solar cells plated in this work showed a more hydrophilic surface behavior with contact angles in the range of 10°–20° at the wafer edge on the rear side whereas in the middle of the cell no contact angle was measurable. On the front side the wetting with a droplet is spreading instantly on the whole surface, confirming the observation that the wrap around occurs faster on the front side than on the rear side. Although, PERC and TOPCon solar cells feature both SiN₆ surfaces, the difference in terms of wettability is evident, but yet unclear and part of ongoing research.

If a both side metallized solar cell is fully immersed into an electrolyte and illuminated a plating process occurs with a deposition on the $n$-type doped side whereas an oxidation

\[ \text{TABLE IV} \]

| Plating | Contacted Interface | Temporary Metal Contact Pressure (N/cm²) | Plating Current Density (A/dm²) | Plating Voltage (V) |
|---------|---------------------|------------------------------------------|---------------------------------|---------------------|
| LIP     | Silicon 6.8 $\times 10^{-3}$ | 2 Ni, 8 Cu | > 20 (Ni and Cu) |
| LIP     | Silicon 122.6 $\times 10^{-1}$ | 2 Ni, 8 Cu | < 5 (Ni) |
| FBP     | Plated Metal 6.8 $\times 10^{-3}$ | 2 Ni, 8 Cu | < 5 (Ni and Cu) |

Optionally, weights were put onto the temporary metal contact to increase the contact pressure between the temporary metal contact and the solar cell.
TABLE V
DEFINITION OF THE CURRENT PATHS $I_{1-3}$ FOR THE RELATION BETWEEN SOURCE CURRENT $I_{\text{source}}$ AND CURRENT OF THE SOLAR CELL $I_{\text{Solar Cell}}$ FOR LIP AND FBP.

| Intended Deposition | $I_{\text{source}} < I_{\text{Solar Cell}}$ | $I_{\text{source}} > I_{\text{Solar Cell}}$ |
|---------------------|---------------------------------|---------------------------------|
| LIP Rear side       | $I_1 = I_{\text{source}}$      | $I_1 = I_{\text{source}}, I_{\text{source}} > 0$ |
|                     | $I_2 = I_{\text{Solar Cell}}, I_{\text{source}} > 0$ | $I_3 = I_{\text{Solar Cell}}$       |
|                     | Deposition on rear              | Dissolution on front            |
| FBP Front side      | $I_1 = I_{\text{source}} - I_2 = I_3$ | $I_1 = I_{\text{source}} - I_2 = I_3$ $(I_2 < 0)$ |
|                     | Deposition on front and rear    |                                 |

Additionally, the intended deposition side and actual deposition or dissolution on each side is mentioned.

Fig. 6. Two cases (1,2) are displayed with zoomed scan images and laser microscopy images at specified positions at the edge of a wafer. Case (1) (a–c) describes LIP with the source current $I_{\text{source}}$. Smaller than the photo generated current of the solar cell $I_{\text{Solar Cell}}$. In case (2) (d–f) FBP was performed in the dark meaning that the solar cells act essentially as a diode. For case (1) on image (c) the removal of the metal showing the LCO is displayed at the edge of the solar cell. For case (2) screen-printed contacts are shown, revealing a change of the contact color to an orange appearance indicating the deposition of Cu.

process, hereby dissolution of metal takes place on the $p$-type doped side. The resulting plating current $I_2$ equals the generated current by the solar cell [17], [23]. In this work two cases can be deduced during LIP (1) and FBP (2) by adding an additional source current $I_1$ (Fig. 2) as displayed in Table V.

For LIP, the external current source, which controls the deposition is smaller than the photo generated current by the solar cell, so that only the source current ($I_{\text{source}}$) is used for the plating process resulting in an exclusive deposition in all wetted areas. In Fig. 6 case (2) the solar cell design Hybrid was used for clarification. The finger in a nonwetted area is typical for a screen-printed finger (d). In the wetted area the finger essentially changes its color appearance revealing the deposition of Cu (e–f). The same effect was also visible for a both side plated solar cell.

The effect of wrap-around of the electrolyte is occurring independently of which side is contacted. As both sides are plated anyway the wetting of both sides itself is not critical. However, if the photo generated current during LIP exceeds the source current, wetting of contacts on the $p$-type doped front side is detrimental as the contacts are dissolved during the plating process. If the $p$-type doped side is not metallized yet the LCO is oxidized, being negligible as this side will be treated with HF before the plating meaning that the $p$-type side should be plated last. If FBP is performed deposition on both sides occurs. At first sight deposition on both sides might be favorable to dissolution of contacts. However, for bifacial plating initially both sides are unmetallized. As the plating time of Cu is exceeding the Ni plating time, the wetted area is greater during Cu plating. Therefore, there is a risk of Cu deposition directly within the LCO, which should be avoided due to strong Cu diffusion into silicon [24] so that the $n$-type doped side should be plated at first. As long as the wrap around is not avoided, plating of the $n$-doped side first followed by the $p$-doped side is suggested, as displayed in Fig. 1, as no contact dissolution would occur on the $p$-type doped side and the additional deposition on the $n$-type doped side would only thicken the wetted contacts causing no harm.

IV. CONCLUSION

In this work, we successfully successively conducted electroplating by directly contacting silicon within local laser contact openings with a temporary metal contact. It has been shown that an inline plating process can be performed for bifacial TOPCon solar cells without the need of a conductive seed layer on at least on side in order to distribute the plating current into the solar cell. Electrical contacting especially of silicon was successfully conducted to perform the plating process but was also identified as a challenging aspect for increasing current density predominantly used on an industrial dimension. An industrial implementation is not fully known yet but improving the contacting is part of further optimization. By pressing the temporary metal contact onto the solar cell, the contacting was significantly improved by reducing the plating voltage from $> 20 \text{ V}$ to $10–15 \text{ V}$ for Cu plating allowing a homogeneous deposition of metal contacts.
Furthermore, contact dissolution was observed during the plating process due to wrap-around of the electrolyte. The origin of the electrolyte wrap-around was identified to be the highly hydrophilic nature of the both surfaces of the used TOPCon samples. A method has been introduced to understand the effects caused by the wrap-around of the electrolyte. The wrap-around causes dissolution in the wetted areas during LIP at high photocurrents on one hand and additional deposition during FBP in the wetted areas on the other hand. Plating of the n-type doped side first followed by p-type doped side allows to neglect the occurrence of the wrap-around with regard to the IV characteristics of the solar cell. Improving the contacting for the plating process as well as preventing the wrap-around of the electrolyte will be part of ongoing work. As a result, industrial TOPCon solar cell precursors were plated with the developed plating process sequence successively on both sides achieving an efficiency of $\eta = 22.5\%$ comparable to bifacial screen-printed reference TOPCon solar cells.

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