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PROGRESS WITH MULTI-STEP METALLIZATION PROCESSES FEATURING COPPER AS CONDUCTING LAYER AT FRAUNHOFER ISE

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ABSTRACT: The present work gives an overview of the activities in multi-step front side metallization for crystalline silicon solar cells featuring copper as conducting layer at Fraunhofer ISE. Different approaches are being followed, the two most important being the deposition of nickel and copper onto printed and fired silver seed layers, or directly onto silicon. The first mentioned technique has been found to exhibit an important potential to reduce the silver consumption per cell. Below 40 mg of printing paste per wafer could be deposited by screen printing, as little as 8 mg by aerosol jet printing and metal inkjet printing. Progress with the challenge of adhesion after plating is presented, although further improvement is still needed. The highest peel force that could be achieved was >1.5 N/mm busbar width. For the second concept, detailed investigations of the contact interface have been done, to tackle the challenge of adhesion. An adaptation of the surface geometry is found to raise adhesion, but only 0.6 N/mm_{BB} have been achieved, which is still insufficient. A silicidation process seems to be necessary to obtain sufficient adhesion.
Keywords: Metallization, Cost Reduction, Electrodeposition

1 INTRODUCTION

The metallization of crystalline silicon solar cells is one of the main cost drivers in the manufacturing process. Screen printing of silver pastes is still the dominating technique, but the need to replace silver with copper to lower cost is increasingly acknowledged.

Electrodeposition techniques are a viable route to achieve this goal, as they are fast, cheap and deliver highly conductive layers. Furthermore, they can be realized at low process temperatures, which is an advantage if copper is to be used.

Copper can be deposited onto a variety of different seed layers that establish the metal-semiconductor contact. The requirements to these seed layers are good mechanical and electrical contact to the wafer, low width and low material consumption. Furthermore, copper diffusion needs to be prevented either by the seed itself, or by an additional barrier. At Fraunhofer ISE, research in the field of multi-step processing for the metallization of crystalline silicon solar cells has been done for many years. Different approaches have been evaluated [1-8], where currently three of these appear to have the highest chances for industrial realization due to process simplicity, performance and costs. These approaches are:

- Nickel and copper plating onto printed and fired silver seed layers
- Direct deposition and contact formation of nickel to silicon, subsequent copper plating
- PVD deposition of seed layers, subsequent copper plating

The first processing scheme has the advantage of relying onto a known and mastered contact formation process. Furthermore, industrial production lines may by operated virtually unaltered following this concept, as merely a plating tool needs to be installed between firing and cell tester, and the printing process itself needs to be adjusted. The second technique has an even higher efficiency and cost reduction potential, but contact formation and adhesion control are more challenging. The third technique allows regress to established techniques from the microelectronics industry and is most interesting for advanced solar cell concepts, where higher manufacturing costs are tolerable.

In this contribution, the latest progress with these processing schemes at Fraunhofer ISE is presented

2 PRINTED AND FIRED SEED LAYERS

The printing process plays a key role in this process sequence, it determines whether it is economically favorable to the standard screen printing process or not.

Several different fine-line printing processes have been investigated during the last years, by Fraunhofer ISE and others. Most give the opportunity to achieve a metal-silicon contact using only very little silver paste. The most extreme case is aerosol jet printing, where about 8 mg of paste (corresponding to ~4 mg of silver) are used per standard 156x156 mm² solar cell in a standard H-grid 3 busbar design. However, none of the novel techniques has achieved industrial realization so far. The lack of processing tools makes the pursue of copper plating onto printed seed layers inattractive to cell manufacturers. This is why presently fine-line screen printing is followed as intermediate step towards a more sophisticated solution. General issues related to the technique can already be addressed in this stage of development, which is beneficial if later on other printing techniques become industrially viable. Furthermore, already with fine-line screen printing, important amounts of silver can be saved, and industrial production lines stay virtually unchanged upon implementation of this metallization route (Fig. 1).

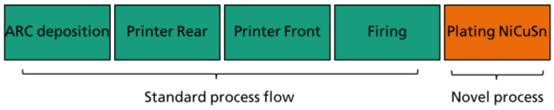

Figure 1: Process flow, starting after PSG etch, using a metallization scheme with nickel – copper – tin plating onto printed seed layers. Green: Standard processes. Orange: Additional processes.

The most critical parameter here is the amount of paste deposited onto the wafer. With a customized screen design, as little as 40 mg of silver paste could be printed onto a full area solar cell, using a special seed paste. In this case, finger widths of about 50 µm could be achieved on a random pyramid texture. With another type of seed paste, the contact width could be reduced even further, to around 35 µm. In this case, paste consumption was slightly higher; between 50-60 mg. Fig. 2 shows a 3D microscopic image of one of the resulting seed fingers.

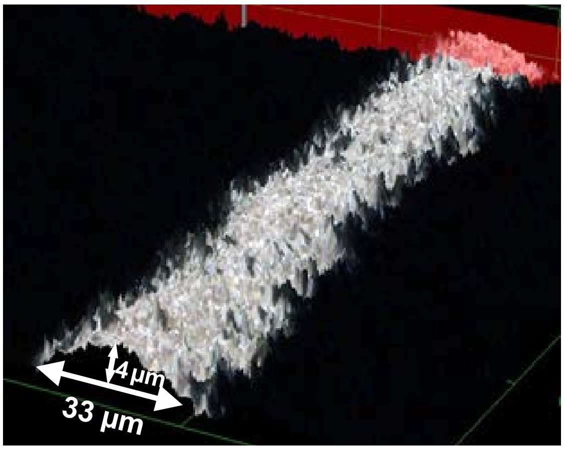

Figure 2: Contact finger created using novel screen and paste customized for seed printing.

Narrower contact fingers and as little as possible paste consumption are key factors to make this metallization variant economically interesting.

One challenge that needs to be addressed with plated contacts comprising copper on printed seed layers is the adhesion and interconnection of the front side contacts. In previous studies an impact of different chemicals commonly found in electrolytic plating baths on the adhesion of solar cell busbars has been shown [9]. By optimizing the process flow and adjusting both paste and plating chemistry, this issue has been found to improve. Fig. 3 shows images of two busbars after peel testing. The first image after standard screen printing, plated with a standard Watt's type nickel electrolyte and a copper electrolyte based on sulfuric acid exhibits very low peel forces below 0.5 $N/mm_{Busbar\text{-}width}$. The printed paste is easily peeled off the silicon wafer. In both cases, capping of copper to allow soldering has been done by plated silver. In the second case, an improved process has been used, allowing for far higher peel forces up to 1.5 $N/mm_{Busbar\text{-}width}$, with the damage mechanism being silicon rip-out of the cell. As this result is not achieved over the entire busbar length, further adjustments are currently under investigation. Simultaneously, detailed investigations regarding the principal interaction between plating chemicals and printing pastes are done.

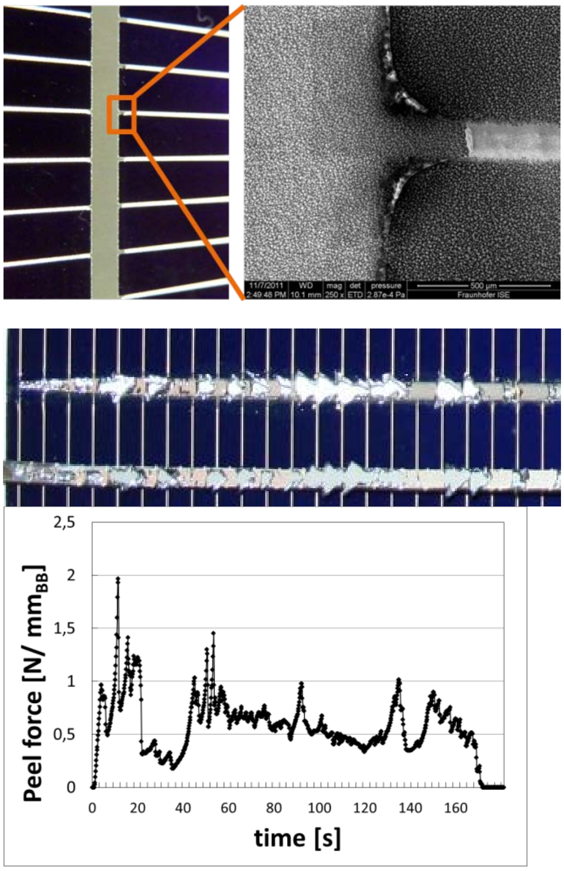

Figure 3: Upper images: Busbar region of a solar cell showing the typical damage mechanism after NiCu-plating with a standard process. Middle image: Result after improved process. Lower image: corresponding peel force diagram.

3 FULLY PLATED CONTACTS

For fully plated contacts, the very high efficiency potential has been demonstrated on a laboratory scale. PERC solar cells (2x2cm²) have been built out of p-type FZ silicon (0.5 Ω cm) with a random pyramid texture, 120 Ω/sq emitter, front and rear SiOx passivation and ARC layer, evaporated Aluminum with laser-fired contacts (LFC, [10]) as rear side contact and masked wet chemical ablation of the front side dielectric layer. Onto the ablated region, several hundred nm of metal have either been evaporated (TiPdAg), or plated (Ni). In both cases, a thermal contact formation step has been done after deposition of the seed layer. The contacts have then been plated with copper.

Table I: IV-results of PERC cells processed with different metallization techniques. Averages are of 14 cells.

Seed&plate process		V_{OC} [mV]	J_{SC} [mA/cm²]	FF [%]	η [%]
TiPdAg +	Avg.	678	38.2	79.6	20.6
Cu-LIP	Best	678	38.8	81.6	21.5*
Ni-LIP +	Avg.	679	38.1	79.6	20.6
Cu-LIP	Best	679	38.8	81.5	21.4*

*independently confirmed by Fraunhofer ISE CalLab PV Cells

Table 1 shows the solar cell IV-results of this study. It can be seen that both top and average efficiency are in the same range for the evaporated and the plated contact system. The best cells have been measured by CalLab PV Cells at Fraunhofer ISE, and a cell efficiency of 21.4 % has been confirmed for the cell with fully plated metallization.

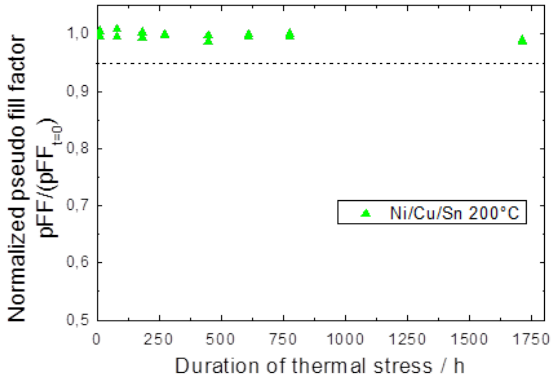

Figure 4: Evolution of the pFF of two solar cells with fully plated metallization under thermal stress of 200°C for more than 1700 h.

To evaluate a possible impact onto the stability of the cell performance due to copper diffusion with this contact system, two of these solar cells have been exposed to thermal stress. The pseudo fill factor (pFF) as measure for the contamination of the junction of the solar cell has been monitored [11]. Fig. 4 shows the evolution of the pFF for the two considered solar cells. It can be seen that even after 1700 h at a temperature of 200 °C, the pFF remains virtually unchanged. This is a strong indication for this contact system to resist cell degradation by copper diffusion into the Si wafer.

As efficiency and long term stability are already on a good level, the main challenge of this contact system remains the mechanical adhesion between nickel and silicon. Different approaches can be followed in this respect. The silicon surface can be modified to give anchoring points for the metal that increase the adhesion. This can, for instance, be done by laser chemical processing (LCP, [12]). However, it has been found that even though very effective anchoring point could be created in the silicon and filled with metal (Fig. 5), the force to peel off the busbar was still rather low (Fig. 6).

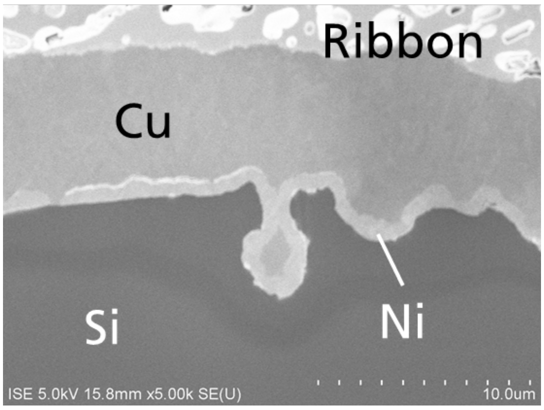

Figure 5: SEM of a cross section of a metal contact plated onto an LCP ablated area. The contact has been soldered and peeled.

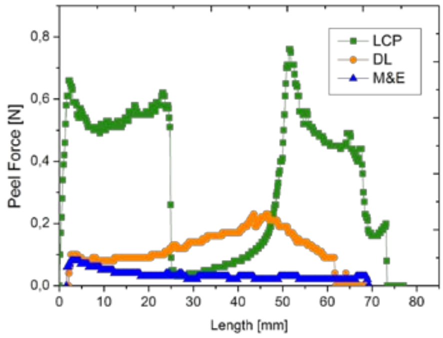

Figure 6: Peel force diagram of cells with a fully plated metallization stack that was created using different ablation techniques, without silicidation process. DL: dry laser ablation. M&E: ablation by masking and wet-chemical etch.

The second way to achieve sufficient adhesion is by the formation of a silicide with the desired properties. Currently, this topic is studied intensively at Fraunhofer ISE. Variations of the silicon substrate, the plating process and the contact formation process have been done and the resulting contact has been studied in detail with respect to its microstructure. First results indicate that certain conditions favor the formation of a silicide, and that this silicide in fact shows a very good adherence to the substrate. However, this study is still in an early stage and could not yet be translated into a process sequence.

4 SUMMARY AND OUTLOOK

In the present contribution, the status of different metallization techniques for crystalline silicon solar cells at Fraunhofer ISE that have the potential to reduce the manufacturing costs has been presented.

For printed seed layers, screen printing as the process that is established in the solar cell industry has been chosen as basis and optimized for the use as seed layer. Line width and paste consumption have already been lowered to as little as 30-40 µm and 40-50 mg, respectively. Further improvements with the amount of paste spent will be in the focus of further investigations. In terms of mechanical adhesion, process adjustments have led to significant progress in this field. While solder stabilities of up to 1.5 $N/mm_{Busbar\text{-}width}$ will already enable first long term testing on a module scale, research on this topic will still continue.

For fully plated metallization systems, the quality of this metallization technique has been shown in an experiment comparing it to evaporated TiPdAg. Additionally, the electrical cell performance has been shown to be unaffected by thermal stress over long durations, indicating a good long term stability of this system in terms of copper diffusion. Examples for current research on improving the adhesion of such plated contacts based on either surface modifications or on silicide growth have been presented. The most promising approaches in this respect will be translated into a process sequence in the future.

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