LOW COST METALLISATION BASED ON NI/CU PLATING ENABLING HIGH EFFICIENCY INDUSTRIAL SOLAR CELLS

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ABSTRACT: This paper describes a viable path for the mass production of Si solar cells that lead to lower cost for PV electrical energy. Systems and modules having solar cells with plated metal contacts benefit from both, a higher solar cell performance as well as significantly reduced consumable cost.

As most advances in industrial solar cell production over the past decades the introduction of plating technology benefits from significant equipment and material improvements. In parallel this road offers to shift the limits with respect to achievable solar cell efficiency by inherent advantages such as the possibility to form narrower metal contacts of excellent conductivity at low cost and the possibility to contact moderately doped Si areas.

Efficiency improvements depend on the degree that other processing steps are adapted to the new degree of freedom in optimization offered by plated contact formation. Efficiency improvement is experimentally demonstrated. Equipment solutions and cost aspects are addressed. Besides good reliability and adhesion of the plated contacts we show efficiency potential exceeding 21% for PERC-type Si solar cells.

Keywords: see enclosed list of keywords

1 INTRODUCTION

Significant improvement in industrial solar cell production has been achieved in the recent decades. Technological improvements in production equipment and materials needed to manufacture efficient Si solar cells enabled drastic cost reduction for solar energy. In parallel the performance of Si solar cells, modules and systems has been significantly improved and supports the cost reduction.

Impressive improvement in equipment development for high throughput laser ablation for inline plating equipment and for electrolytes enabling reliable and cost-effective high throughput plating processes were necessary. Today a transition from printed Ag paste contact formation to laser ablation and reliable directly plated contacts with Cu as main conducting material is feasible and offers a number of advantages. The most prominent advantages are: significantly reduced consumable cost and the potential to achieve an improved solar cell performance due to reduced shading losses and the ability to contact improved emitters with lower dopant concentration. In the following we discuss equipment improvement that was required to enable low cost mass production of plated contacts. We address the process requirements to achieve better solar cell performance with plated compared to printed contacts and demonstrate increased efficiencies on conventional Al-BSF and advanced PERC-type solar cells. This and parallel papers on this conference [1-4] demonstrate that well adherent contacts can be formed in a simple processing sequence requiring only one inline plating equipment. After analyzing the cost of ownership (CoO) for this technology an outlook including potential for further improvement will be given.

2 PLATED SI SOLAR CELLS

2.1 Equipment improvement

Plating technology had been and is continued to be industrially applied [5-8] to manufacture highly efficient solar cells. Still a widespread use was so far prevented by rather complex processing sequences that were needed to build these devices or by equipment that did not allow yet simpler and more efficient processing at a low cost. In the recent years it has been shown that it is sufficient to apply at the end of the solar cell process (after emitter formation, surface passivation and rear contact formation) a laser ablation step selectively removing the dielectric coatings at those areas where contacts should be formed [9-10]. In those ablated areas contacts are subsequently plated as a metal stack. Ni at the interface is followed by Cu plating a thin capping layer. The complete metal stack is subsequently annealed at a moderate temperature to improve adhesion and to reduce contact and grid resistance. Ni is forming Ni silicide areas when an adequate temperature range is used. Ni and Ni silicide layers act as an effective barrier to Cu and prevent in-diffusion of Cu atoms into the Si which could otherwise harm the p-n junction performance and increase recombination losses in the Si bulk. Cu is an inexpensive alternative to Ag. Cu is highly conductive but available at significantly lower cost. As capping layer our preference is to use a very thin Ag coating. Even 100-200 nm of Ag are sufficient to prevent major oxidation during the annealing step. Thus soldering conventional interconnection ribbons with solder coating to the busbar regions is no problem after finishing the solar cell. The difference in front contact formation to printed Ag paste contacts is shown in Figure 1.

Ag paste contacts	Plated contacts
Print or double/dual print Ag paste selectively	Laser ablate selectively dielectric layers
Dry the paste contacts	Plating sequence (LIP-Ni, LIP-Cu, capping)
Fire the paste contacts	Anneal

Figure 1: Difference in metallisation between printed and plated contact formation

Production equipment for the described simple processing sequence has been developed in the recent years and offers today a road to high throughput at low cost. Adequate laser ablation of 100-160 very narrow (5-20 µm) contact finger lines and wide (1-2 mm) busbar regions requires the availability of very fast (repetition rate, scanning speed) and well adapted [2] laser equipment. Pulse duration, pulse shape and wavelength of the laser have to be well adapted to the ablation process in order to enable high solar cell performance while at the same time ensuring good contact adhesion and reliability. Since short first adequate laser platforms for industrial mass production are commercially available. This was not the case a few years ago when the throughput needs required using several laser platforms in parallel in order to get the required throughput but therefore increased the invest cost significantly. Adequate pulse shapes were not available yet for mass production.

It required significant improvement in the plating process to offer today adequate compact plating equipment hosting three subsequent plating steps and the required pre-treatment for the deposition of Ni, Cu and Ag in only one plating tool. An essential advantage of the equipment developed at RENA is that the rear sides and therefore also the contacts on this rear sides of p-type solar cells are kept dry during this process while the plating current is passed in reverse direction through the solar cell by illuminating it from the front side that is exposed to the respective electrolytes.

Keeping the rear side of the solar cells dry is in our view essential to the success of a mass production tool for plating of Al-BSF and PERC-type Si solar cells. If plating electrolytes interact with the rear contacts of the solar cell those might degrade it noticeably. Efficiency losses of more than 1% absolute have been observed when exposing Al and Ag paste rear contacts to the plating chemistry. The interface/overlap regions of Al and Ag-based pastes show discoloration. The glass components in the pastes can get partially dissolved and the Al contact might act as a sponge storing electrolyte traces even after annealing the contact stack on the front side of the solar cell. These effects are not wanted when aiming for reliable modules in mass production. Furthermore, if the cathode passing the plating current through the solar cell gets in contact with the plating solutions it will plate as well. This would change over time the contact properties between cathode and solar cell rear contacts in a negative way and make inline processing impossible unless the cathode remains permanently exposed to the electrolytes. But even then the cathode would steadily grow and require replacement or cleaning cycles.

The approach keeping the rear side of the solar cell dry and passing the plating current through cathodes touching the dry solar cell rear contacts is unique and relies on patented technology [11]. An alternative to light induced plating (LIP) might be electroless Ni plating. Keeping the wafer rear side dry to prevent rear contact degradation of the solar cellis preferred there as well. However, electroless plating is more difficult to control, has lower plating rates and typically requires higher processing temperatures for the electrolytes.

The plating processes classified as 'light induced plating' have to ensure that the solar cell receives sufficient light to pass the desired plating current in reverse direction over the pn-junction of the solar cell. A number of challenges had to be overcome to come to an equipment solution as commercially available since short. Significant improvement equipment-wise and with the electrolytes used for this application enabled to significantly reduce the plating time that is required to form narrow and well conductive contact fingers while ensuring excellent contact adhesion.

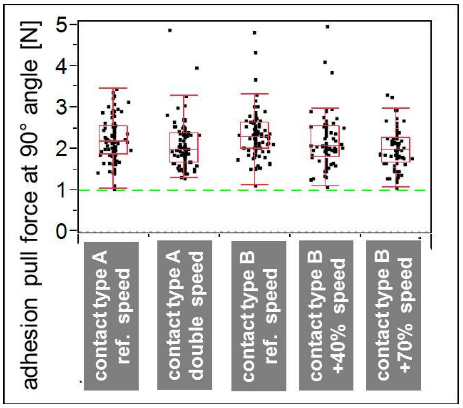

Figure 2: Comparative study of equipment and process modifications with respect to contacting the solar cell and passing a higher plating current through the solar cells while increasing in parallel the plating speed. No significant influence on the studied adhesion of interconnection ribbons soldered to the busbar regions has been observed.

An example for such an improvement is given in Figure 2. The influence of two sets of contacting schemes (cathode contact to the Si solar cell) as well as the influence of increased plating speed on adhesion of soldered interconnectors is compared.

Even though the result seems not spectacular it is a major improvement with respect to high throughput inline processing. Doubling the plating speed and improving in parallel the reliable contact formation have been essential to come to conditions that allow high throughput processing in a single plating equipment and reducing the processing cost and initial invest.

For each improvement in the equipment the processing conditions and the electrolytes it is essential to check whether contact properties of the plated contacts are affected and still acceptable for industrial solar cell production. In this case (Figure 2) it is obvious that doubling the process speed was feasible without negative impact on contact adhesion. This was tested by soldering conventional interconnection ribbons (1,5 mm * 0,15 mm; 20 µm Sn62%Pb36%Ag2% solder coating) to the busbars using a semiautomatic stringer from SOMONT. On each of the three busbars 6 areas are soldered simultaneously. Subsequently, these interconnectors are pulled off under a 90° angle using a semiautomatic XYZtec pull tester. We are pleased to find the weakest link in this destructive pull test within the Si and not at the metal-Si interface or within the metal stack. The failure mechanism is in most cases Si wafer breakage at sufficiently high pull force. Large pieces of the Si solar cell are still attached to the interconnection ribbons after pull testing.

The pull test results in Figure 2 suggest no major difference in contact adhesion when changing the contacting scheme and increasing the plating rate. At the same time also electrical performance of the plated solar cells remained unchanged too.

In the meanwhile RENA succeeded by other process and equipment modification to double the plating speed another time without negative impact on adhesion and solar cell performance. Those improvements were essential to make plated contact formation in inline production industrially applicable and cost-effective. The achieved improvement allows the involved partners an ambitious schedule (see Figure 3) for the introduction of laser ablation and plating technology into mass production.

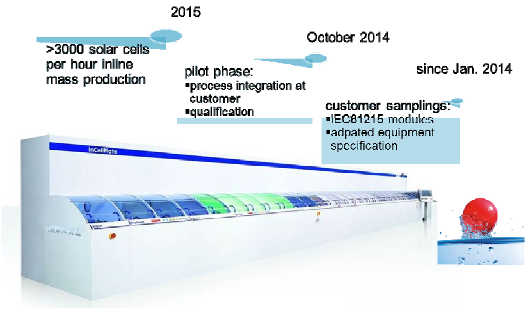

Figure 3: Inline plating equipment integrating pre-treatment, LIP-Ni, LIP-Cu and immersion or LIP Ag capping in one plating sequence and schedule towards introduction in industrial mass production.

An essential step in this schedule were accelerated aging tests of solar cells and first modules with Cu based plated contacts formed with the mentioned simple process flow. IEC61215 test results with respect to thermal cycling and damp heat (assumed to be most relevant for testing metal contacts and interconnection) have shown no significant change in solar cell performance of these modules after full test procedure. More detailed results of these tests will be reported in parallel papers on this conference and elsewhere [1, 3, 12].

2.2 Solar cell performance improvement by plated contact formation

Having finally adequate equipment for all required process steps available it is useful to address the performance improvement of Si solar cells that can be achieved when adapting the preceding process to the new opportunities offered by plating. This improvement in solar cell efficiency and module or system power can be harvested on top of the significantly reduced consumable cost for metallization.

Process-wise the main advantages of plated contact formation are:

- Very narrow contact fingers (< 15 µm laser opening; 30-35 µm plated width) in reliable mass production achievable.
- Geometry and surface finish allow to significantly further reduce the effective shading losses (optical width < 20 µm) caused by contact fingers in modules.
- Very low contact resistance even to moderately doped Si regions with doping atom concentrations of 10^{19} at/cm^3.
- No porosity within contact cross section.
- Suited for advanced (well passivated) high efficiency emitters and homogeneous emitters with high sheet resistance (low dark saturation current density Joe).

It is obvious that it cannot be expected to harvest the performance advantages of plated contact formation without adapting the overall solar cell process to the new degrees of freedom offered by this metallization technology.

The most evident and easy accessible advantage for plated contacts are the reduced shading losses. An example is given with the experimental results for conventional industrial Si solar cell precursors on textured p-type CZ-Si wafers having a 85 ohm/sq. front emitter, a PECVD SiN_x:H coating as antireflective passivation layer on the front and Al BSF on the rear side.

All solar cells in the experimental split have seen the same processing sequence including rear side printing and firing for Al BSF formation. The only difference is that the group with double printed front contacts went prior to firing additionally through the Ag paste printing and drying process, The group with plated contacts went after firing and Al BSF formation through laser ablation, plating and thermal anneal of the LIP-Ni/Cu+immersion Ag metal stack. Inline plating equipment and a conveyor belt furnace with nitrogen atmosphere have been used to form the contacts. The results are shown in Table I.

Table I: Comparison of screen printed Ag and plated (LIP-Ni, LIP-Cu, Im-Ag) contact formation on 156 mm industrial CZ-Si solar cell precursors with 85 Ω/sq. emitters optimised for printed contact formation.

20 solar cells per group	J_{sc} [mA/cm²]	V_{oc} [mV]	FF [%]	Eta [%]
Double print Ag paste	**37.6 ± 0.2**	**637.2 ± 0.9**	**79.7 ± 0.4**	**19.1 ± 0.2**
LIP Ni/Cu plated contacts	38.5 ± 0.1	636.5 ± 0.4	79.6 ± 0.2	19.5 ± 0.0

There are two significant differences in the solar cell performance results of the two compared groups: The short circuit current density Jsc is significantly higher for the plated contacts while the 1 σ standard deviation is lower for all parameters of the plated solar cells. Reason for the better Jsc are the reduced shading losses for the plated fingers (BB width identical). The narrower distribution of all solar cell parameters is something we see through all our experiments. It is likely that it has to do with the fact that plated contact formation has no problems to contact also lower doped areas of the solar cell in a reproducible way. Screen printed contacts require to have very high P surface concentrations in the emitter regions exceeding 10^{20} P atoms/cm^3 in order to achieve low contact resistance values. Furthermore, using more but narrower fingers in case of plating reduces emitter resistance losses and makes also there the solar cell less dependent on emitter sheet resistance variation over the surface.

It would be wrong to assume that plated solar cells will in all cases result in 0.4% abs. efficiency improvement over printed solar cells applying Ag pastes. It would be wrong as well to assume that improvement can be only achieved from reduced shading losses and that it would not be required to adapt earlier process steps like emitter formation and passivation.

Screen printed Ag paste formation has made big improvements over the recent years. It is today possible to print narrower contacts than the 80 µm fingers shown in Table I. Double print and dual print technologies allow pushing the limits also with respect to paste consumption. Advanced Ag pastes allow in principle contacting emitters with sheet resistance values up to 100 Ω/sq. Thus it is possible to come with screen printed technology to performance values similar to the ones shown for plating in Table I. However, it should be noted that with plating it is possible to contact emitters that are more advanced than those optimized for screen printing technology. Thus the task to achieve the best possible or most economic performance gain for plated contacts is leaving potential aside when precursors optimized for screen printing are supplied. In that case the advantage is limited to the benefits from reduced finger width. Well conductive plated Cu-based contacts have a typical finger width of 30-35 µm. This cannot be achieved by printed contact formation in mass production without accepting throughput and/or yield losses and additional cost. As long as emitters in the range of 60-80 Ω/sq. are used it is also not necessary to have fingers that are significantly narrower than 60-80 µm. The resistive losses in the emitter are still not as high that they would require using significantly more fingers (additional shading losses to balance the resistive losses in the emitter). However as soon as emitters with 100-130 Ω/sq. are considered for industrial mass production it is necessary to increase the finger number and to make the fingers as narrow as possible to benefit from those emitters. More fingers can thus be used to the lower the chance that variations in sheet resistance over the wafer surface will have significant impact on resistive losses in the emitter region. But more fingers are only a good choice and compromise when they are narrow. With plated contact formation up to 150 fingers (30-35 µm width) can be a good choice when emitters in the range of 120 Ω/sq. sheet resistance are combined with those narrow fingers.

Furthermore, plated contact formation allows reducing the dopant surface concentration N_s. High N_s causes significant recombination losses in the surface near region of the emitter. Emitters with moderate doping concentrations N_s are used in most high efficiency solar cell concepts. They lead to significantly lower recombination current densities J_{oe} when passivating the surfaces well. Such emitters can be beneficially contacted by plated Ni/Cu contacts even for P surface concentrations of $N_s \sim 10^{19}$ P atoms/cm^3 – more than an order of magnitude lower than for emitters that are required for screen printed contacts ($N_s > 10^{20}$P atoms/cm^3).

In order to obtain the desired emitter conductivity, those moderately doped emitters are therefore deeper than emitters with the same sheet resistance and very high P surface concentrations. These deeper emitters result in wider process windows for laser ablation and Ni silicide formation during the annealing step.

More advanced emitters than those used today for solar cells with printed Ag paste contacts are therefore a logical step when optimizing the overall processing sequence for solar cells with plated contacts. The benefit of improved emitters and the improved front contacts becomes more pronounced when the solar cell is not strongly limited and therefore dominated by recombination losses in the bulk or at the wafer rear sides. Passivated rear sides as used in PERC- and PERL-type Si solar cells combined with good Si wafers offer today a road to achieve efficiencies exceeding 21%.

To demonstrate this performance improvement potential we used PERC-type solar cell having advanced 120 ohm/sq. emitters with SiOx/SiNy:H passivation stacks on front and rear sides, respectively. The plating sequence indicated in Figure 1 has been applied on those precursors too.

Measurement:	Jsc [mA/cm²]	Voc [mV]	FF [%]	Eta [%]
@ RENA	39.8	662.1	79.7	**20.99**
@ FhG-ISE CalLab after LID stabilisation	39.4	662.1	79.8	**20.83**

Table II: So far best PERC-type CZ-Si solar cell with plated Ni/Cu/Ag contacts.

The result of in-house measurements and the independently confirmed result measured by FhG-ISE CalLab after light soaking and stabilizing the best solar cell are reported in Table I. Further experiments with partners attempting to exceed 21% efficiency are running. It becomes obvious from these results that plated contact formation offers a road to higher efficiency industrial solar cells in mass production. In particular for PERC-type solar cells there is further room for overall process improvement enabled by the plated front contact technology. So far, firing processes for paste contacts were typically dominated by the front contact requirements to achieve low contact resistance with Ag pastes firing through dielectric coatings. For plated front contacts there is an additional degree of freedom for process optimization as front contact formation is independent of the rear contact firing temperature. Thus, it seems possible to modify the firing temperature for local or full BSF formation independently. This is for instance of particular interest when using AlOx passivation layers on the rear side of PERC-type Si solar cells [13, 14] where high firing temperatures have negative impact on the passivation quality of an AlOx/SiNx:H passivation stack. Using a rear side passivation technology implementing good AlOx surface passivation might lead to considerably higher solar cell performance as the recombination losses become then dominated by front side and bulk recombination. In that case advanced emitters on the front side as enabled by plated contacts allow assessing the full efficiency potential of such rear side passivated solar cells.

Laser technology, plating equipment and electrolyte chemistry have made progress that allows PV manufacturers to improve the performance of their products while at the same time cutting down the production cost.

Table III: Average solar cell performance of so far best group with laser ablated and plated 156 mm * 156mm mc-Si Al BSF solar cells.

Jsc [mA/cm²]	Voc [mV]	FF [%]	Eta [%]
35.6	621	79.1	**17.5**

Recently, RENA made also progress with respect to plating on mc-Si solar cell precursors with Al-BSF. Laser ablation on iso-textured mc Si instead of alkaline textured CZ-Si with random pyramids seems on a first view more challenging because of the big variation in the surface topology and crystal orientation. That is why we applied in first experiments advanced laser conditions in cooperation with FhG-ISE [2].

The solar cell performance results (best group) and adhesion results (three ablation conditions) shown in Table III and Figure 4 indicate that it is possible to achieve both, good contact adhesion and respectable solar cell performance values at the same time when forming plated Cu based contacts as described above. Pull test forces are again limited by solar cell breakage and not by metal-Si adhesion.

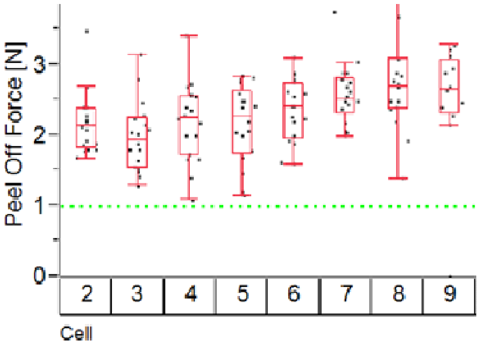

Figure 4: Pull test (90° pull angle) results after soldering interconnection ribbons to the busbars of mc-Si solar cells.

3 ECONOMIC ASSESSMENT

In a partnership with MacDermid as electrolyte supplier and Innolas as laser equipment supplier first economical assessment of a technology package offering a throughput of 3000 wafers/hour with one laser ablation tool, one inline plating machine and one inline annealing furnace has been done. This assessment is based on differences in metal contact formation under the following assumptions:

The reference process is a screen printing process for 156 mm wafers with similar throughput. The Ag paste consumption per solar cell front side is assumed to be in the range 80-100 mg. The plated metal deposit is assumed to be as well in a range of 80-100 mg per solar cell. The screen printing (single print assumed) and front side drying equipment is replaced as an up-grade of an existing production line by three additional pieces of equipment (laser ablation, plating annealing) leading to an additional invest that needs to be depreciated and paid back by the lower consumable cost and potential efficiency improvement.

It is assumed that the compared solar cells have the same rear contacts and that a firing furnace for Al paste firing will be still needed in both cases. The solar cell rear sides are therefore either Al-BSF or PERC/L-type. An efficiency gain of 0.3% abs. for plated contact formation is assumed after optimizing the overall processing sequence for plated contact formation. To assess the benefit from improved efficiency a cost of 40 €Ct/W_p has been assumed for CZ-Si solar cells.

Ag paste prices are mostly depending on Ag prices. These prices have seen big fluctuations in the recent years. Only three years ago Ag prices have been more than double as high as today. For our cost calculations we assumed a Ag paste price of 600 €/kg.

Taking all cost including cost for plating into account we see a net cost saving of 3.1 €-Ct per solar cell under the above taken assumptions.

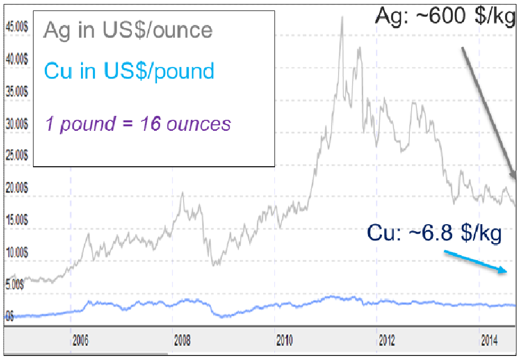

Figure 5: Ag and Cu price evolution over the last 10 years and today's price in €/kg. Ag pastes cost (including add-on cost for paste manufacturing) strongly depend on the silver raw material cost. Cost for plating is practically independent of the much lower Cu price.

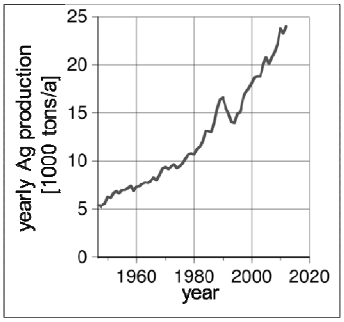

Figure 6: Increase in yearly Ag production over time. PV production is today consuming the largest share of this production and would run in Ag supply problems when continuing to consume Ag pastes as of today.

The benefit to have solar cells and modules with higher efficiency justifies the higher invest and leaves a net benefit for plated contact formation. The payback period for the invest is smaller than 2 years in case of a new production line (no invest for front side printers and dryers) and smaller than 3 years in case of an up-grade of an existing production line in the metallization area.

There are good reasons to believe that Ag price fluctuations (see Figure 5 and Figure 6) and increases will happen again. PV applications consume today already the largest share of the industrial Ag produced in the world and are predicted to cause a shortage in Ag when continuing to grow in the overall yearly consumption as can be anticipated from predicted PV market growth. Thus, Ag paste consumable cost could also easily double compared to our assumption of 600 Euro/kg above. This would force manufacturers much more urgently to follow their own predictions in the international technology roadmap for PV [15] with respect to replacing Ag paste consumption by Cu based contact schemes.

Cost assessment on a more detailed level is better done by taking the influencing factors of each individual business partner into consideration. RENA is open to discuss such data with partners intending to implement plating technology in their production and suggest a piloting phase (reduced throughput as suggested in Figure 3) as first step in that direction.

4 OUTLOOK AND CONCLUSIONS

Significant progress in the development of adequate process technology, equipment and electrolytes is reported and enables a transition from rather expensive Ag paste contacts to laser ablated and directly plated Ni/Cu contacts in mass production of Si solar cells.

It is shown that a simple processing sequence for plated contact formation leads to reliable and adherent metal contacts that offer to reduce shading losses, resistive losses and emitter recombination losses in industrial solar cells.

Efficiency improvement compared to screen printed solar cells has been demonstrated on industrial Al-BSF precursors with emitters that are optimized for screen printed contact formation. Here only reduced shading losses helped to realize an efficiency improvement of 0.4% in average. However, more synergy is expected when adapting earlier processing steps like emitter formation to the possibilities of plated contact formation.

The demonstration of this synergy resulted on a PERC-type precursor with an excellent independently confirmed solar cell efficiency of 20.82%. This solar cell was LID stabilized. New results exceeding 21% efficiency are in preparation.

The economic assessment of plated contact formation suggests advantages over printed contact formation even at moderate Ag price levels as present at this moment in time.

Further improvement can be expected from plated contact formation when decoupling the need to form busbar regions by laser ablation from the finger formation process. Busbar regions are so far a considerable share of the overall metallisation area of the solar cell. The maximum Voc that can be obtained for advanced Si solar cells is clearly limited by the metallisation share on the Si surface because these areas dominate recombination losses at the surfaces. However, there is no need why busbar areas would have to form electrical contact to the Si areas. Their main purpose is to transport current that is generated in the non-metallised area and collected by the fingers with the help of interconnection ribbons (typically soldered to the busbar regions) to the next solar cell in the PV module.

There are several approaches that are compatible with plating in which it is possible to form conducting busbars differently than by plating. As discussed earlier [16] such approaches significantly improve the throughput in laser ablation and plating. Furthermore, they have the potential to improve the solar cell and solar module efficiency significantly. Approaches of particular interest are those that reduce shading losses, reduce Voc losses and apply more than three busbar or current collecting structures. With approaches like smart wire interconnection, conductive adhesives or low temperature pastes for busbar formation (preferably without Ag paste) potentially in combination with light harvesting interconnector structures it seems even possible to achieve solar cell efficiencies on PERC-type solar cells of 22%. With an increased number of interconnect wires or busbars it is feasible to apply even narrower fingers of < 20 µm width because conductivity requirements are reduced and laser opening can be as narrow as 5 µm.

5 ACKNOWLEDGEMENT

Part of this work has been financially supported within the funded projects LasVeGaS, SONNE, KuLI and rEvolution by the German ministry BMU. We gratefully acknowledge this support.

6 REFERENCES

[1] N. Bay et al., '*Reliable contact formation for industrial solar cells by laser ablation and Ni/Cu plating*', Proc. of this conference

[2] A. Brand et al., *'Tailored low damage laser contact openings for large area high efficiency solar cells'*, Proc. of this conference.

[3] A. Letize et al., *‘Pilot scale production and reliability testing of solar cell modules based on a low cost copper electroplating process’*, Proc. of this conference.

[4] A. Mondon et al., *‘Plated nickel-copper contacts on c-Si: from microelectronic processing to cost effective silicon solar cell production’*, Proc. of this conference.

[5] N. Mason et al., *‘Laser grooved buried grid silicon solar cells from pilot line to 50 MWp manufacturing in ten years’*, Proc. PV in Europe, Rome, Oct. 2002, pp227-229

[6] W.P. Mulligan et al., Sunpower Corp., *‚Metal contact structure for solar cell and method of manufacture‘*, US patent 7388147 B2

[5] N. Mason et al., *‘Laser grooved buried grid silicon solar cells from pilot line to 50 MWp manufacturing in ten years’*, Proc. PV in Europe, Rome, Oct. 2002, pp227-229

[6] www.silevosolar.com

[7] O. Schultz-Wittmann et al., ‚*Fine line copper based metallization for high efficiency crystalline silicon solar cells*, Proc. 27th EUPVSEC, Sept. 2012, pp596-599

[8] www.sunpreme.com

[9] R. Russell et al., *‚A simple copper metallization process for high efficiencies and reliable modules’*, Proc. 27th EUPVSEC, Sept. 2012, pp538-543

[10] A. Lachowicz et al., *‚NOx-free solution for emitter etch-back’*, Proc. 27th EUPVSEC, Sept. 2012, pp1846-1850

[11] M. Gutekunst et al., RENA GmbH, *‘Apparatus and method for providing electrical contact for planar material in straight-through installations’*, EP2152939 B1

[12] J. Bartsch et al., *‘Simple and reliable processes for creating fully plated nickel–copper contacts’*, to be published in Photovoltaics International Iss.25, 2014

[13] R. Sastrawan et al., ‚*Industrial production of multicrystalline silicon solar cells with efficiencies above 18%’*, Proc. 8th SNEC, Shanghai, May 2014

[14] D. Pysch et al., ‚*Implementation of an ALD-AlOx PERC-technology into a multi- and monocrystalline industrial pilot production’*, Proc. of this conference

[15] http://www.itrpv.net

[16] J. Horzel et al., ‘*Different concepts of implementing a directly plated front side metallization into industrial solar cell mass production’*, Proc. 28th EUPVSEC, Sept./Oct. 2013, pp1374-1379