Low cost high efficiency metallisation using Ni/Cu based contacts for next generation industrial solar cells

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Abstract: To help photovoltaic energy gain a larger share in the world's total energy mix it is essential to further reduce the cost of solar generated energy and in parallel to enable mass production at a scale 100-1000 times higher than today. Plated metal contacts may play an essential role to produce industrial c-Si solar cells and modules with higher output power at reduced cost per $\text{Watt}_{\text{peak}}$. The technology enables manufacturing reliable metal contacts with excellent adhesion when pull-testing on conventionally soldered interconnection ribbons and is also adequate for thin wafers. An average efficiency of 19.6% is reported for industrial p-type Al-BSF CZ-Si solar cells with light induced plated Ni/Cu contacts formed after laser ablation. IEC61215 testing on modules fabricated from these solar cells is in progress. For PERC/PERL-type Si solar cells a peak efficiency of 20.83% has been independently confirmed by FhG-ISE CalLab. Cu plating technology allows for significantly reduced consumable cost while paving the way towards higher c-Si solar cell and module performance in industrial mass production. A key technology for sustainable PV growth is introduced and positively evaluated in an economic assessment.

Keywords: Ni and Cu plating; Light induced plating; reduced shading; contact adhesion

1 Introduction

The factors limiting the efficiency of industrial Si solar cells have shifted in the recent years [1-3]. Today it is possible to benefit with advanced Ag pastes from shallower emitters and improved contact properties. For PERC- and PERL-type Si solar cells the passivated rear sides and local BSF regions have improved the situation further while in parallel Si material quality has improved as well. Thus by now, for state of the art industrial Si solar cells the front emitter, its passivation and the metal contacts are again efficiency limiting factors when aiming at efficiencies beyond 21%. At the same time the cost for contact formation by screen printed Ag pastes is one of the highest cost shares in industrial solar cell production - dominated by the fluctuating Ag cost that is difficult to control and predict. On a longer term it is even a threat that the availability of Ag and its accessibility at affordable cost would become an issue if annual world-wide solar cell production grows further as in recent years.

The approach proposed by RENA is to replace printing, drying and firing of Ag pastes by the selective laser ablation of dielectric layers followed by light induced plating of Ni and Cu, immersion plating of a thin Ag capping layer and subsequent thermal annealing of the complete metal stack.

Solar cells with metal contacts formed in that way have a similar efficiency potential as laboratory Si solar cells with lithographically defined evaporated contacts [3, 4]. In the following, very good solar cell efficiencies are reported for p-type CZ-Si solar cells with Al-BSF as well as with PERC-type rear sides. It is shown that excellent adhesion is achieved when soldering conventional interconnection ribbons to the plated busbars and performing pull tests. The solar cell performance distribution is very narrow and allowed RENA GmbH and its partners to fabricate first 60 cell solar modules that undergo IEC61215 test conditions (thermal cycling, damp heat).

Assessment of solar cell performance, reliability and economic aspects is clearly in favor of applying the developed plating technology for Cu based contacts. So far we have no hint for disadvantages when using Ni/Cu plated contacts in future mass production of Si solar cells. The equipment of RENA GmbH is according to our knowledge the only in-line equipment keeping the rear side of the wafer dry during surface conditioning and plating. It is deemed to be essential to prevent exposure of the rear contacts to the cleaning and plating chemicals when aiming for reliable high efficiency industrial Si solar cells in mass production. There are no obstacles for scaling up that technology to future needs of industrial solar cell manufacturing lines.

2 Experimental

2.1 Solar cell processing

The basic processing sequences for the solar cell types on which we report here are given in Fig. 1 for both, Al-BSF and PERC/PERL-type Si solar cells with plated contacts. All results are on p-type CZ-Si wafers with a base resistivity ranging from 1 - 4 Ωcm. Three new pieces of equipment replace printers and dryers typically used for front contact formation with Ag pastes in conventional production lines. Laser ablation equipment opens the front dielectric layer selectively where metal should be plated on the thus exposed area of the emitter. Opening widths in the range of 5-15 µm can be reproducibly achieved for subsequent contact formation in the finger regions. Inline equipment of RENA GmbH is used to clean the laser ablated areas prior to subsequent light induced plating of Ni and Cu. The inline equipment is unique in the sense that the rear sides of the wafers that are contacted to apply a cathodic potential are kept dry during the complete plating process. The metal stack on the front sides of the solar cells receives an additional capping layer – a very thin immersion Ag coating in most of the reported experiments. The capping layer facilitates soldering and prevents oxidation of the Cu surfaces. The third equipment is an in-line annealing furnace that anneals the metallization stack at a moderate temperature in nitrogen atmosphere.

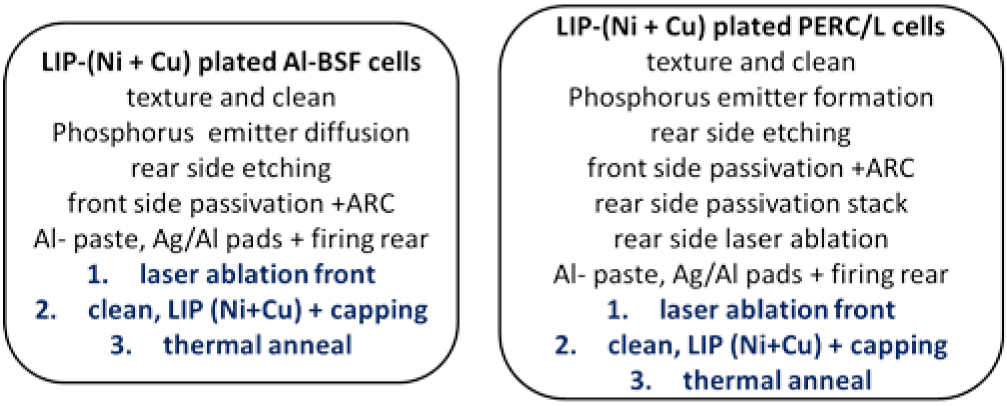


Fig 1: Principle processing sequences for Al-BSF and PERC/PERL-type solar cells with plated contacts. In both cases the metallization of the front side requires three pieces of equipment.

The plated contact fingers have a typical width of 25-35 µm after finishing the solar cell process. This is considerably narrower than for conventional production lines relying on paste metallization. The annealing process assures that the Ni-Si interface offers a reliable, well adherent contact with low contact resistance even when emitter P surface concentrations of only 10^{19}P atoms/cm^3 are used. This in turn gives the potential to improve emitter and front surface passivation beyond existing limitations for printed contacts. For the Al-BSF solar cells reported below conventional emitters in the range of 65-85Ω/sq. with high P surface concentration (>10^{20} P/cm^3) have been used and are therefore not optimized for plating yet. For the PERC-type solar cell reported below passivated emitters (thermal SiOx) with higher sheet resistance (~120 Ω/sq.) and reduced P surface concentration have been applied.

2.2 Ni/Cu plated contact formation on Al-BSF precursors

The outlined plating process has been optimized at RENA GmbH with respect to equipment and process parameters for laser ablation, the individual plating steps and subsequent thermal annealing using industrial precursors. These precursors benefit from a dense PECVD SiN_x:H antireflective coating (ARC) on the wafer front side that prevents ghost plating. The front emitters on the external precursors are optimised for Ag paste contact formation and therefore not optimum yet for solar cells with plated contacts. Nevertheless, it is easily possible to contact such emitters by plated contact formation.

The laser ablation process has to be well adapted to the surface texture and dielectric coatings. Deep damage regions need to be avoided. However, the dielectric layers have to be completely ablated at the intended regions. Overlap of laser pulses has to be tuned to result in the desired opening pattern.

RENA GmbH has compared plated and screen printed contacts on Al-BSF precursors that have been entirely metallised (front and back) at RENA GmbH. The average sheet resistance of the emitters for these precursors was about 80 ohm/sq and the emitter profile optimized for Ag paste contact formation.

The obtained results shown in Table 1 indicate that decent fill factor FF and solar cell efficiency results have been obtained for both, printed and plated contact formation at RENA. Screen printed contact formation used 80 µm wide fingers and three busbars on the 156 mm Cz-Si solar cells. The busbar width of 1,5 mm was identical for Ni/Cu plating and Ag paste printing. Thus the difference in Jsc is mainly a result of reduced shading losses for the narrower contact fingers of the plating process. The average results for 20 cells per group indicate a narrower performance distribution and 0.3 to 0.4 % abs. higher efficiency for plated contact formation. Even for solar cell manufacturers having more advanced paste printing processes plated contact formation offers the potential to reduce shading losses, emitter losses and recombination losses significantly while improving FF further even for emitter sheet resistance values up to 120 ohm/sq.

	Jsc [mA/cm2]	**Voc [mV]**	**FF [%]**	**pFF [%]**	**Eff. [%]**
screen print	37.6 ± 0.2	637.2 ± 0.9	79.7 ± 0.4	83.2 ± 0.1	19.1 ± 0.2
Ni+Cu plating	38.5 ± 0.1	636.5 ± 0.4	79.6 ± 0.2	82.3 ± 0.1	19.5 ± 0.0

Table 1: Comparison of average solar cell performance of solar cells screen printed and plated (Ni and Cu light induced plated) contacts on conventional p-type 156 mm CZ-Si solar precursors with RENA Al-BSF rear contacts and with industrial homogeneous 80 Ω/sq. emitters.

Recently, RENA GmbH performed samplings for several customers. Precursors were again industrial Al-BSF solar cells with Al paste and Ag paste (pads for interconnection) contacts on the rear side. In one approach solar cells were laser ablated and Ni/Cu contacts were formed as described above. Module manufacturing (60 cells per module) has been done at FhG-ISE and IEC 61215 testing is in progress there.

The precursors in that sampling run had homogeneously diffused emitters (sheet resistance: ~65 Ω/sq.) with high P surface concentration (suited for screen printed contacts).

(400 cells)	Jsc [mA/cm²]	Voc [mV]	FF [%]	Eta [%]	pFF [%]
Median	**38,1**	**640,6**	**80,3**	**19,6**	**82,7**
Average	**38,1**	**640,4**	**80,3**	**19,6**	**82,8**
std. dev.	**0,2**	**1,2**	**0,2**	**0,1**	**0,2**

Table 2: Average results for the main group of the CZ-Si (156 mm, p-type, 1-3 Ωcm, pseudo-square) solar cell sampling run. Laser ablation, one-sided LIP-Ni, LIP-Cu, 200 nm immersion Ag (capping) and in-line anneal have been performed by RENA GmbH.

In this sampling, both J_{sc} and FF outperform screen printed contact formation. To further improve J_{sc} and V_{oc} it is essential to adapt the emitter (reduced P surface concentration) and passivation. Nevertheless, we believe that the obtained results are excellent for industrial Al-BSF precursors. To obtain high average FF and Jsc values at the same time is only possible when using narrow fingers as achievable with plating. The use of Cu as main conducting material allows for a favourable cost of ownership as will be discussed below. Performance distributions for FF and J_{sc} for the main group of this sampling run are shown in Fig 2. The distributions are narrow indicating that the process can be controlled very well. It is very reasonable to assume that a plating process leads in mass production to much narrower performance distributions than high volume processes applying screen printing technology. The obtained distributions indicate that FF values beyond 81% seem to be feasible in near future. So far 80.9% on two of the solar cells is the highest result achieved without varying the number of fingers yet. With a shunt resistance of 20kΩcm^2 and a pFF of 83% series resistance and in particular line resistance (Grid resistance = 50mΩ) is limiting at the moment. Narrow finger lines of 30 µm width allow to form more fingers than applied so far. This is in particular useful, when moving to optimised, well passivated 120 Ω/sq. emitters to exploit the full potential of Cu plated contacts.

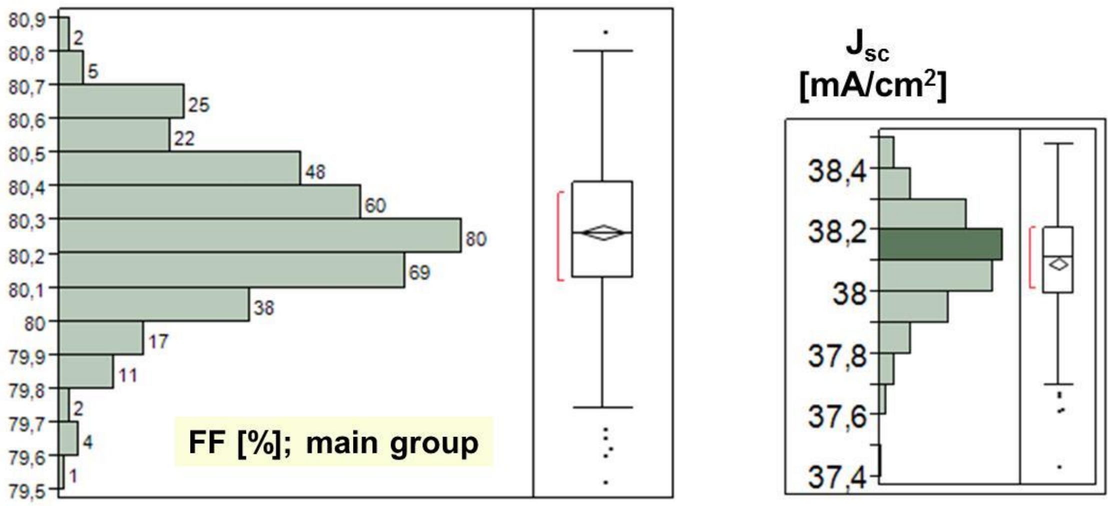


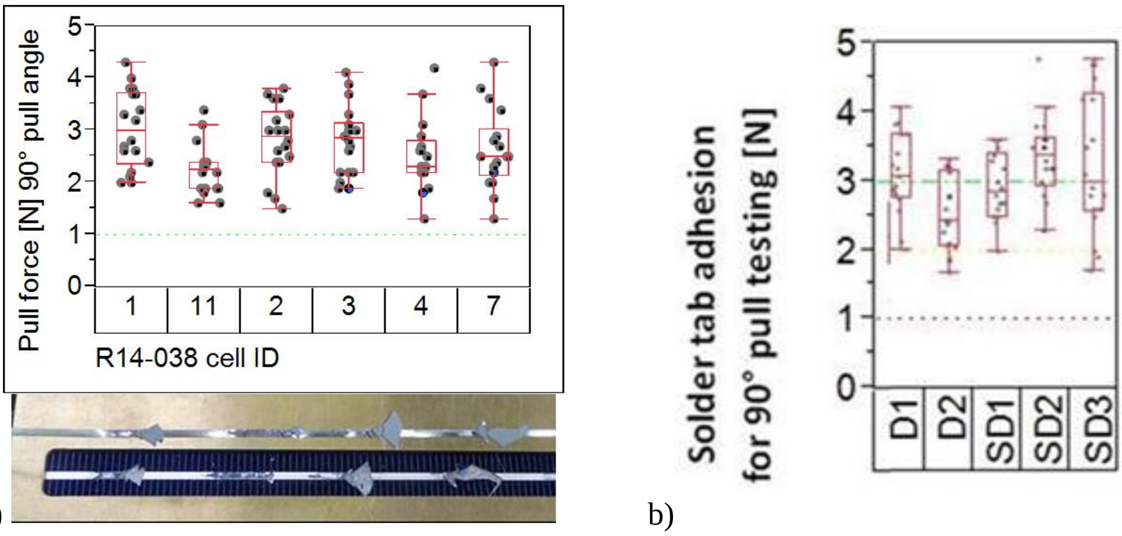
Fig 2: Fill factor (FF) and short circuit density J_{sc} distribution for the main group (~400 cells) of a sampling for a customer that resulted in the fabrication of modules that currently pass IEC 61215 test conditions.

A very important optimization result is that it is absolutely essential to prevent that the rear contacts of the industrial precursors get in contact with pre-treatment or plating solutions. In case that the Al paste/AgAl paste overlap regions of the rear sides of the solar cell got wet during the plating process, the FF is degraded significantly reducing efficiency up to more than 1% absolute. We attribute this to corrosion effects at the overlap regions that can be seen by discoloration of these regions. But also in general, in all cases in which pastes containing glass frit are applied for rear contact formation interaction of paste contacts with electrolytes or pre-treatment solutions should be avoided. The interaction may dissolve or etch the glass frit at least partially. As a result adhesion of the rear contacts and contact resistance of these contacts may suffer significantly if the rear sides are not kept dry.

According to our knowledge, RENA GmbH is the only equipment manufacturer offering in-line plating equipment that keeps the rear contacts of the solar cell dry during the plating processes. The reported sampling has been performed on 5 lane production type inline equipment with one-sided plating processes at RENA GmbH in Freiburg for all individual plating steps.

2.3 Adhesion and soldering for module interconnection

Good electrical solar cell performance is only one pre-requisite of plating technology to gain market shares from screen printing metallization. At least as important is the adhesion of the contacts and their solderabilty for conventional module integration. The processing sequence that we applied allows soldering solar cells after the in-line thermal annealing step that follows the plating process. Semi-automatic soldering equipment from Somont GmbH is applied at RENA to co-solder conventional solder-coated and fluxed Cu ribbon (1.5 mm width, 0.15 mm height; 20 µm coating by 62%Sn/36%Pb/2%Ag) on 6 locations of each of the three busbars. The soldered interconnection is then tested by semi-automatic pull testing equipment from XYZTEC. Under a pull angle of 90° the ribbons are pulled off and the force is recorded. The wafer is kept on the chuck by a metal plate covering the wafer surface except the busbar regions (see photo in Fig 3a on the bottom). RENA GmbH assesses for each of the 18 soldered regions the maximum pull forces and the respective 'failure mechanism'. The distribution and mean value of the pull force values are analysed and visualised for each wafer in graphics as shown in Fig 3. For the plating campaign reported in Table 2 and Fig 2 wafers had been picked and soldered at different moments of the campaign to verify in advance to module fabrication (stringing) that the plating is adequate to easily enable module fabrication. The pull testing results are shown in Fig 3a). As visible in the photo the adhesion is limited by Si solar cell breakage (failure mechanism). The pull tester rips off large pieces of the Si wafer around the soldered areas. The resulting mean pull forces are therefore only giving a lower limit for the adhesion of the plated metal to the Si surface. However, mean pull forces of 2-3 N are generally considered to be sufficient for reliable module stringing. In Fig 3b) Ni/Cu plated and screen printed contact solar cells have been soldered and the pull strength is compared on the same precursor. Within the natural fluctuation for pull test data that is in both cases limited by wafer breakage and not by metal-silicon adhesion the pull force distributions are comparable.



a) b)

Fig 3: Pull testing of laser ablated and plated (LIP-Ni/Cu) 156 mm CZ-Si solar cells; a) solar cells taken at different moments from the sampling run reported in Table 2 and Fig 2. Top: analysed pull force distributions. Bottom: photo indicating the failure mechanism; b) Analysed pull test data comparing plated (D1, D2) and screen printed (SD1-SD3) precursors from the same supplier.

2.4 Cu plated contacts on advanced passivated emitters and PERC-type rear sides

In order to have the full benefit from plated contact formation it is advantageous to adapt the solar cell process to the additional degree of freedom in contact formation for plated contacts compared to screen printing contact formation. The overall efficiency optimum shifts for plated contacts towards higher emitter sheet resistance and lower P surface concentration in the emitter regions. The higher sheet resistance and therefore lower overall P doping (integrated over emitter depths) becomes possible by the narrower but still highly conducting contact fingers. Thus it is feasible to form more fingers while reducing overall shading and emitter resistance losses. The lower P surface concentration becomes applicable by the significantly lower contact resistance of nickel silicides compared to Ag paste contact interfaces. It is easily possible to contact P surface concentrations down to 10^{19} P/cm^3 without having negative impact on the fill factor FF. This allows at the same time to implement better surface passivation and to have lower recombination losses in the emitter region. Thus the emitter dark saturation current density can be reduced that much that it is no more dominating the overall recombination losses. In rear side passivated solar cells this gives another boost to the overall efficiency improvement for that solar cell type.

Jsc [mA/cm²]	Voc [mV]	FF [%]	Eta [%]	pFF [%]
39,4	662,1	79,8	20,83	82,0

Fig 4: So far best independently confirmed (FhG-ISE CalLab) PERC-type solar cell with Ni/Cu plated contacts applying the RENA plating process indicated in Fig 1. The PERC-type precursors have an advanced 120 Ω/sq. emitter with P surface concentrations below 10^{20} P/cm^3 and adequate surface passivation on both surfaces of the p-type 156 mm CZ-Si wafers.

Fig 4 gives a first glimpse on what is possible when optimizing the overall processing sequence for plated contacts. The 120 Ω/sq. emitter is not fully optimized yet, as the emitter depth is about 0.5 µm while an optimum can be expected at about 1 µm. Thus, the P surface concentration should be further decreased to take full advantage of plating. Nevertheless, the performance of the so far best independently confirmed (FhG-ISE CalLab) PERC-type solar cell that has been plated at RENA indicates that high J_{sc} values and good FF values are not a contradictory requirement for solar cells with plated contacts. Internally, at RENA the highest efficiency measured for that cell type is in the meanwhile 20.99%. It is believed that further optimization of the overall process will soon result in solar cell conversion efficiencies exceeding 21% when applying the RENA plating process (LIP-Ni/Cu + immersion Ag followed by thermal annealing) to more advanced PERC-type or PERL-type precursors with industrial relevance.

3 Economic considerations

The benefit of Cu plated contacts compared to Ag paste contacts is multiple and depends on the following key elements:

- Cost for Ag paste contact formation. Despite impressive technological achievements in the fields of printing technology and paste improvement there remain major obstacles for this technology:

    - The Ag price is volatile and speculation-driven. Shortage of commercially produced Ag is likely to become another significant cost-driver as PV production capacity continues to grow as predicted.
    - Indirect cost because advanced solar cells remain limited in their maximum efficiency potential because printed Ag paste front contacts continue to impose limits on emitter formation and specific contact resistance to lowly doped emitter regions ($< 10^{20}$ P/cm^3).
- Solar cell architecture and degree of optimization for the specific contact formation method (individual optimization for both, printing and plating required to fully assess the respective advantage for plated contacts). → Effective efficiency gain and cost for plated contact formation.
- Differences in the total CoO for both technologies, including consumable cost, invest, yield, labor cost and other associated cost factors.

In consequence the evaluation of the offered metallization technology may lead to different results when doing it at different moments in time and at different manufacturing sites.

In the evaluation of RENA GmbH Cu plating is today the better choice compared to Ag screen printing or other technologies applying Ag paste. Assuming modest Ag consumption of 100 mg per 156mm wafer the significantly lower consumable cost and the higher performance of modules applying Cu plated contacts justifies the higher initial invest for the production line. This holds the more if Ag prices will increase again to levels as seen two years ago or increase even further. An increase in Ag cost and therefore as well an increase in Ag paste cost is very likely when the global PV production is increasing as can be anticipated. The PV industry is already today consuming the largest share of the global yearly Ag production. This share will further increase and become a burden on expansion plans for c-Si technology when continuing with business as usual. That is why the majority of PV experts from industry being asked in the international roadmap for PV (ITRPV) predict a significant change in the metallization of crystalline solar cells in the years to come. Early adaptors of Ni/Cu plating technology will not suffer from the Ag price turbulences that can be predicted today already. They will have advantages over others that have no equipment for plating available yet and that have not adapted and qualified their production processes for plating yet. RENA therefore recommends advanced PV manufacturers and in particular those that are vertically integrated to take the step now towards a low cost, high performance, high throughput metallization technology that allows them sustainable growth and increasing market shares in future.

The authors encourage all PV manufacturers to perform their own economic evaluation for the offered metallization technology based on industrially relevant production volumes and after adapting the solar cell process to the advantages of the offered laser ablation and Ni/Cu plating technology. The biggest advantages and economic benefit is expected for those customers that have already the most advanced solar cell architectures (as for instance PERC-type technology). RENA offers in addition to Cu plating technology equipment solutions for advanced texturing, advanced cleaning, advanced single side etching, advanced single side polishing, emitter etch-back, selective emitter formation and if desired also for inline application of a phosphorus source (deep emitter formation). It is believed that those solutions can successfully contribute to an overall process optimization for solar cells and modules with Cu plated contacts.

4 Conclusion and outlook

RENA GmbH has together with its partners Innolas (for laser ablation) and MacDermid (for adequate electrolyte development) worked on an offer for the PV industry and research organisations enabling them to take the next step towards solar cells and modules with higher performance at lower cost. It is suggested to replace printed Ag paste contact formation by laser ablation of dielectric layers and subsequent one-sided light induced plating of Ni and Cu and a finish by a capping material enabling soldering after thermal anneal of the complete metal stack. The suggested new technology results in the following advantages: a) significantly reduced consumable cost, b) improved solar cell and module performance, c) independence of Ag price fluctuations, d) better compatibility with high performance solar cell architectures such as optimized industrial PERC- and PERL-type Si solar cells.

Excellent adhesion of metal contacts with the described metal stack on laser ablated fingers and busbar regions has been demonstrated. The busbar regions have been interconnectedby conventional soldering to form 60 cell modules. The pull forces when pulling off the conventional interconnection ribbons showed no disadvantage compared to screen printed Ag paste metallization. Pull forces were in both cases limited by Si wafer breakage at sufficiently high pull force values.

The 60 solar cell modules that have been manufactured at FhG-ISE are currently in climate chambers to pass IEC61215 test conditions. Intial values during this test look promising and do not show hints that the Cu based plating technology would have disadvantages over Ag paste metallization.

On 156 mm p-type CZ-Si Al-BSF precursors with homogeneous emitters (65-85 Ω/sq.) average solar cell performance values resulted in 19.6% efficiency with outstanding average FF values of 80.3% for average short circuit current densities clearly exceeding 38 mA/cm^2. Best FF values for plated contacts reached up to 81% FF. On an advanced PERC-type precursor (156 mm p-type CZ-Si) with homogeneous 120 Ω/sq. emitter efficiencies up to 21 % have been achieved with the best independently confirmed (FhG-ISE CalLab) efficiency being 20.83%.

RENA and its partners are ready to offer equipment solutions for plated contact formation to solar cell manufacturers and research organisations and to support their first steps into a new era for advanced industrial solar cell metallization. RENA offers as well to potential customers sampling runs that support their decision to acquire adequate plating equipment.

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