Plating for passivated-contact solar cells

Sven Kluska, Thibaud Hatt, Benjamin Grübel, Gisela Cimiotti, Christian Schmiga, Varun Arya, Bernd Steinhauser, Frank Feldmann, Jonas Bartsch, Baljeet Singh Goraya, Sebastian Nold, Andreas A. Brand, Jan Nekarda, Markus Glatthaar & Stefan W. Glunz, Fraunhofer Institute for Solar Energy Systems ISE, Freiburg, Germany

Abstract

Passivated-contact solar cell designs, such as TOPCon or silicon heterojunction solar cells (SHJs), enable cell efficiencies greater than 24%, and are promising candidates for the next revolution in mass production after the passivated emitter and rear cell (PERC). Plated metallization (Ni/Cu/Ag or Cu/Ag) fits well with new constraints on low-temperature processing and the combination of low material costs and highly conductive bifacial metal grids for these types of solar cell. For TOPCon solar cells the combination of bifacial laser contact opening (LCO) and Ni/Cu/Ag plating allows highly conductive grid lines with low contact resistivities for a boron emitter on the front side and TOPCon on the rear side. LCO achieves low contact recombination, which enables further reduction of the TOPCon layer thickness. Bifacially plated i-TOPCon solar cells were fabricated at Fraunhofer ISE, achieving maximum cell efficiencies of up to 22.7% with significantly reduced cost of ownership (COO) compared with bifacial screen-printing metallization. Plating has always been considered a highly interesting option for metallizing SHJ solar cells. Many research groups (ISE, CSEM, ASU, UNSW) and companies (Sunpreme, Kaneka) are working on plating development, while GS Solar already uses plating in production. Fraunhofer ISE has established an innovative process sequence called *NOBLE* (native oxide barrier layer for selective electroplating), which allows bifacial plating of SHJ cells. The NOBLE sequence includes physical vapour deposition (PVD) of metal seed layers, which enable reliable mechanical and electrical contact, homogeneous plating current distributions/heights and low COO.

Introduction

The PV industry passed a milestone in recent years, in migrating from multicrystalline aluminium back-surface field (Al-BSF) technology to the mono passivated emitter and rear cell (PERC) design. This technology shift was made possible by continual wafer, cell and module technology improvements and significant reductions in production cost for PERC technology. Furthermore, the Al-BSF design has reached its solar cell efficiency limitations, in contrast to the still steeply rising cell-efficiency learning curve for industrial PERC technology; the range of the efficiency potential of PERC solar cells is estimated to be 24% [1]. Passivated-contact solar cells – such as tunnel oxide passivated-contact (TOPCon) [2] and silicon heterojunction (SHJ) cells – are promising candidates for enabling solar cell efficiencies to be achieved in mass production beyond the efficiency limit of PERC. Various research institutes and solar cell manufacturers have in fact already demonstrated solar cell efficiencies beyond 24%. This technology transition will most likely occur with a migration from p-type to n-type mono wafers.

> "A major task in passivated-contact solar cell development is to further decrease production costs."

Passivated-contact solar cells are already achieving high cell efficiencies, and have been well established for many years in mass production at various solar cell manufacturers (SunPower, Panasonic, Sunpreme, ...). However, a major task in passivated-contact solar cell development is to further decrease production costs. Back-end processes are a significant cost driver for TOPCon and SHJ solar cells. Screen printing is the conventional and well-understood metallization technology employed for PERC solar cells, and is also typically used for metallizing TOPCon and SHJ solar cells. The bifacial grid design, which is common for these solar cell types, significantly increases the material costs, now that silver (Ag) or silver–aluminium (AgAl) pastes must be printed on the front and rear sides of the solar cell in order to also achieve low grid resistances on the rear side. If increasing PV growth is forecast to a TW market scale, the silver consumption turns out to be a massive cost driver for solar cell production (1TW would use 100% of today's annual worldwide Ag production [3]).

Replacing Ag with copper (Cu) would enable raw material costs to be reduced by a factor of 100. The plating of Cu or stacks of Ni/Cu/Ag is a well-known technology in the PV industry. This paper shows in the following sections that Cu-plated contacts align well with all back-end technology requirements of TOPCon and SHJ solar cells. Plating technology holds the potential to significantly reduce production costs for passivated-contact solar cells. The main advantages of Cu-plated contacts for these solar cell designs are:

- Low cost of ownership (COO)
  - Low material costs
  - Synergetic cost reductions, such as TOPCon thickness reduction
- Compatibility with existing mass-production back-end tool equipment
- Potential for efficiency gains
  - Narrow contact width

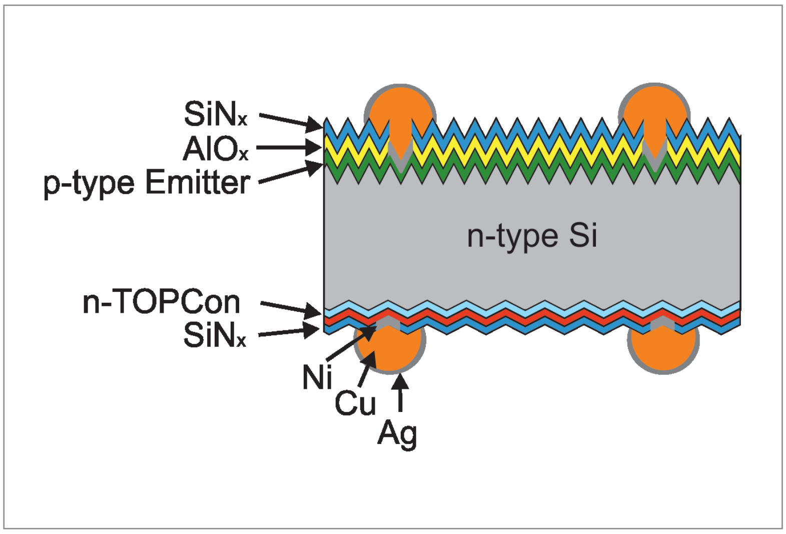

Figure 1. Schematic of a TOPCon solar cell with bifacially plated Ni/Cu/Ag contacts.

- o Highly conductive finger at low process temperatures
  - o Low contact resistance and contact recombination

Plating metallization for TOPCon solar cells

Bifacially plated Ni/Cu/Ag metal contacts can help to further reduce manufacturing costs and increase the cell efficiency of industrial TOPCon (i-TOPCon) solar cells. The replacement of Ag with low-cost Cu as the main conducting material enables a reduction in the back-end production COO for bifacial solar cells with metal grid patterns on both sides.

A robust process sequence for plated contacts on PERC solar cells has been developed over the last few years [4,5]. The combination of laser contact opening (LCO) and inline plated Ni/Cu/Ag has allowed high-quality contact properties with low COO for PERC solar cells using existing mass-production tools. The implementation of plated Ni/Cu/Ag contacts for bifacial TOPCon solar cells is based on these developments. The technological benefits of LCOs and plated Ni/Cu/Ag are:

- Low contact resistivities on n-type TOPCon layers and lightly boron-doped emitter

- Low contact recombination on
  - o TOPCon: allows further reductions in TOPCon thickness, because of shallow laser-damage depth
  - o boron emitter: enables V_{oc} improvements

- Narrow contact width (<25μm) with low line resistivity

The concept of the n-type TOPCon solar cell was introduced by Feldmann et al. in 2013 [6]; it features a boron-doped front-side emitter and a

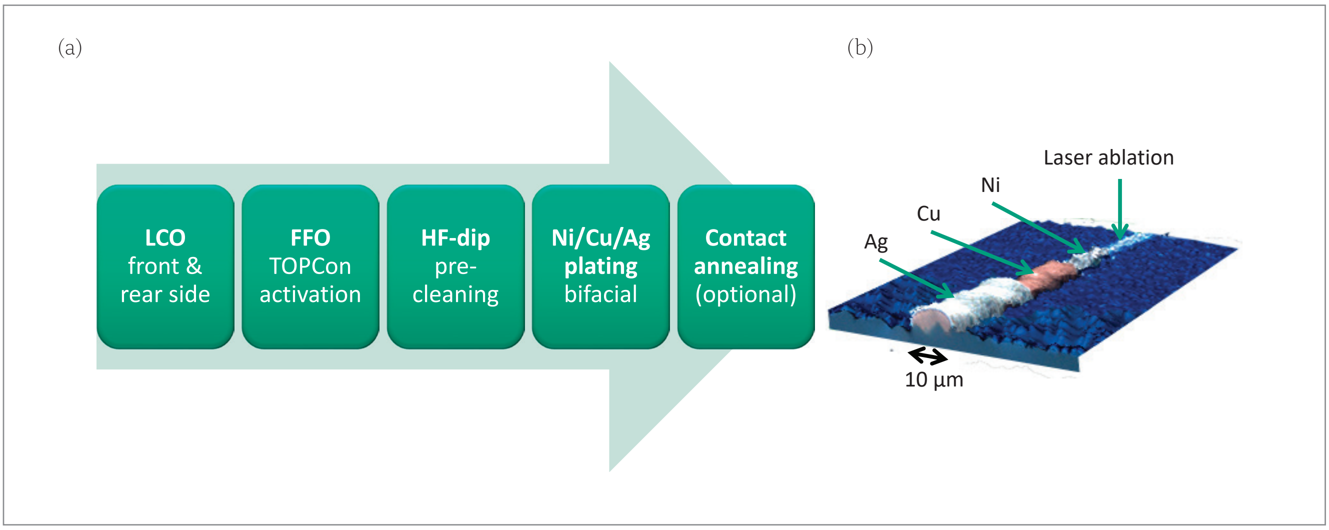

Figure 2. (a) Back-end process flow for bifacially plated TOPCon solar cells. (b) Composite microscope image of the contact finger after LCO, Ni (1µm), Cu (10µm) and Ag (0.5µm) plating.

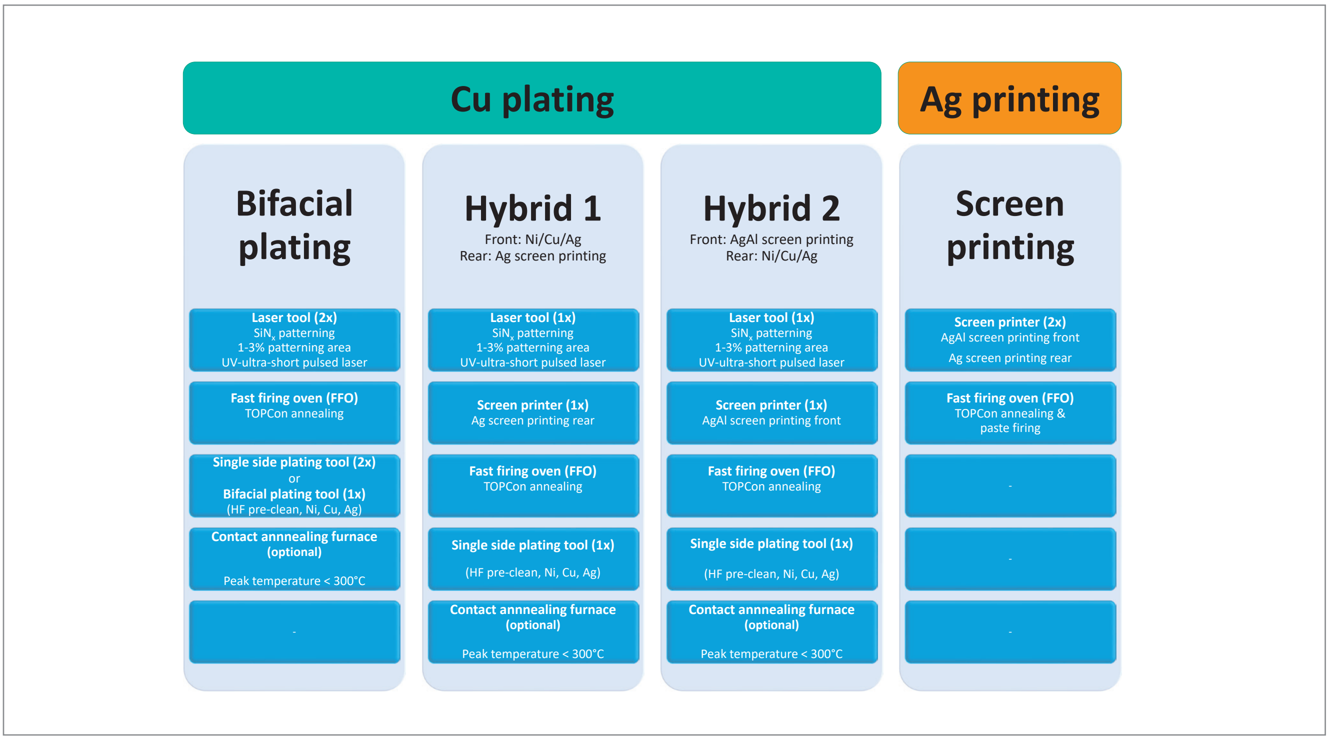

Figure 3. Overview of back-end solutions for i-TOPCon solar cells with plated Ni/Cu/Ag contacts.

passivated contact on the rear side. Since the first introduction of this technology, the definition of industrially feasible process sequences was the main focus for technology developments, starting from PECVD, LPCVD and sputter developments for TOPCon deposition, and then moving on to metallization processes that enable high cell efficiency and low COO.

The metallization of i-TOPCon solar cells poses new challenges compared with Ag or Al screen-printing processes in the well-understood PERC process sequence. Low contact recombination (preferably using thin TOPCon layers), low contact resistivities (on boron-doped emitters and TOPCon layers), narrow finger width and low COO are desired. In particular, the combination of low contact resistivities and the avoidance of spiking through the TOPCon layer turns out to be a major topic for screen-printing metallization [7]. The combination of laser structuring and plated Ni/Cu/Ag is a viable alternative in the ongoing developments of screen-printed i-TOPCon solar cells [8,9].

Process sequence and back-end solutions

Plated contacts for passivated-contact solar cells were introduced in recent years by companies such as SunPower and Tetrasun [10]. The first introduction of plated contacts in TOPCon solar cells at Fraunhofer ISE were aimed at contacting

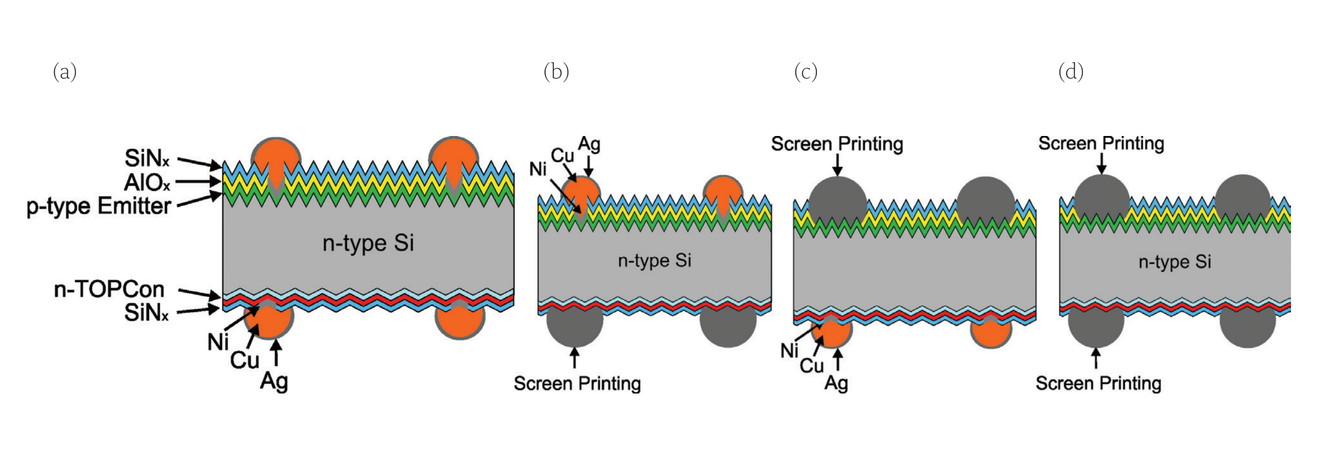

Figure 4. Schematics of i-TOPCon solar cells: (a) with bifacially plated Ni/Cu/Ag contacts; (b, c) hybrid designs (Hybrid 1 and Hybrid 2) with plated and screen-printed contacts; (d) with screen-printed contacts.

		V_{oc} [mV]	J_{sc} [mA/cm^2]	η [%]	*FF* [%]	*pFF* [%]
Screen printing	Best	690	39.9	22.7	82.3	83.5
	Average	686	39.9	22.4	81.8	83.4
Hybrid 1	Best	692	40.3	22.7	81.6	83.4
	Average	688	40.3	22.7	81.8	83.4
Hybrid 2	Best	689	39.8	22.4	81.8	83.0
	Average	688	39.8	22.3	81.4	83.3
Bifacial plating	Best	690	40.4	22.7	81.4	83.5
	Average	687	40.3	22.4	80.7	83.1

Table 1. Measured *I–V* parameters for i-TOPCon solar cells (masked measurement area 145×145mm^2, total cell area 158.75×158.75mm^2).

the boron-doped emitter to enable cell efficiencies of up to 23.4% [11]. These attempts were followed by the introduction of laser-defined plated Ni/Cu/Ag contacts on both sides for bifacial i-TOPCon solar cells [12]. Fig. 1 illustrates the design of an i-TOPCon solar cell with bifacially plated Ni/Cu/Ag contacts.

The back-end process sequence for TOPCon solar cells with metal-plated contacts developed at Fraunhofer ISE is shown in Fig. 2(a). The plated contacts are defined by local laser ablation of SiN_x anti-reflection coatings (ARC) using ultrashort pulse laser systems. The combination of UV-ps laser systems and textured surfaces guarantees reliable contact adhesion because of the laser-induced nano-roughness on the pyramid sides [13,14]. TOPCon layer activation can be performed by fast-firing oven (FFO) annealing after laser ablation. The FFO activation can also be exploited as laser-damage annealing in order to further reduce contact recombination [15]. HF pre-cleaning before plating removes the process-induced and native oxide layer to ensure clean silicon–nickel contact interfaces.

Various plating tool designs (inline plating, batch plating) are applicable to bifacially plated TOPCon solar cells. The solar cells presented in this work are plated using an inline plating process of a thin Ni interface layer (<1μm), a Cu (1–10μm) layer, and an Ag surface finish (<0.5μm). Only electroplating processes – such as light-induced [16], forward bias [17] or direct contact plating [18] – were used to deposit the metal layers. Fig. 2(b) shows a composite microscope image of the contact finger cross section after each process step.

The process sequence shown in Fig. 2 is an industrially feasible approach for integrating plated Ni/Cu/Ag metal contacts in i-TOPCon solar cells. The contact metallization can be either a bifacially plated contact design or a combination of plated and screen-printed contacts. Fig. 3 shows three back-end sequences with metal-plated contacts on the boron-doped emitter, on the TOPCon, or on both sides. The *Hybrid 1* and *Hybrid 2* designs refer to combinations of screen-printed and plated contacts on either side of the solar cell.

Solar cell integration and contact characteristics

Industrially manufactured i-TOPCon precursors without metallization were used to demonstrate plated i-TOPCon solar cells employing the four back-end processing options shown in Fig. 3. The precursors were taken out of the regular mass-production line and optimized for screen-printed metallization. There were no specific changes in design or in processing for all the precursors before metallization. The reference group with bifacially screen-printed metal contacts was fully processed at the manufacturer's site; for the hybrid approaches,

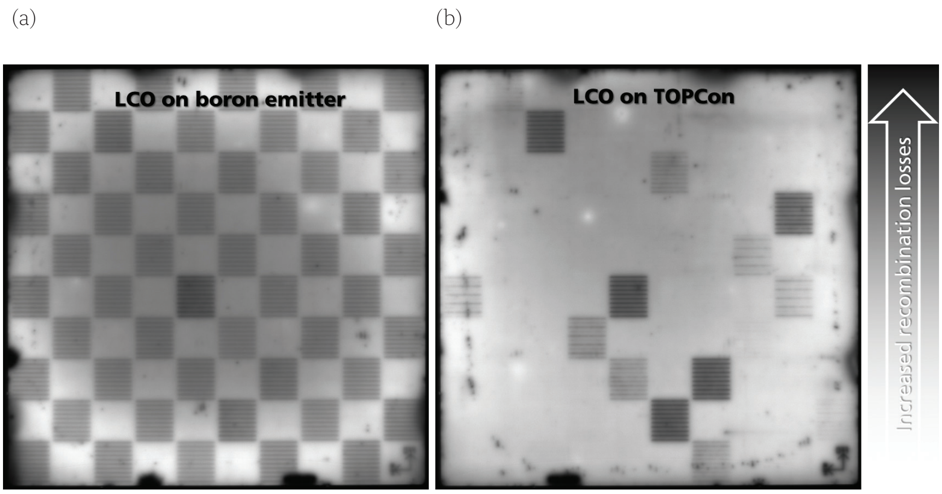

Figure 5. PL measurements for characterizing the contact recombination of samples with lasered test fields of LCO variations: (a) on the boron-doped emitter; (b) on TOPCon. Note that the same LCO parameter variation was performed on both images, but only parameters with high laser powers are visible in the case of TOPCon.

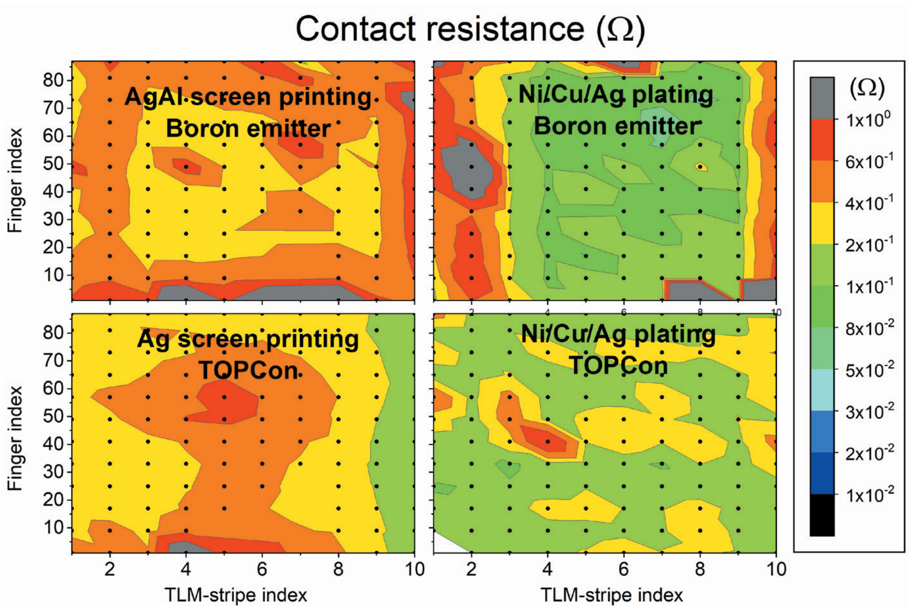

Figure 6. Measured contact resistance mapping of cut i-TOPCon precursors (158.75×158.75mm² cut into 10 strips) with boron-doped emitter or TOPCon layers and either screen-printed or metal-plated contacts. The black dots represent the positions of the TLM measurements. Note the difference in mean contact width of 40µm for screen printing and 25µm (LCO width: 18µm) for plating.

the screen printing and firing/TOPCon activation was also covered by the manufacturer.

The plating metallization for all process groups with metal-plated contacts was realized at Fraunhofer ISE, as was the TOPCon activation of the bifacial plating precursors. Since the FFO/TOPCon activation process at Fraunhofer ISE was not optimized for these precursors, the implied V_{oc} (the cell V_{oc} potential before metallization) was about 5–10mV below that of the optimized FFO/TOPCon activation process at the manufacturer's site.

Table 1 shows the measured *I–V* parameters of the fabricated i-TOPCon solar cells (see Fig. 4). The measurements were performed using a 145×145mm² shadow mask because of edge artefacts due to shipping and manual handling. All the processed groups yield mean cell efficiencies between 22.3 and 22.7%. The best screen-printing reference achieves a solar cell efficiency of 22.7%, while the best back-end groups Hybrid 1 and 2, with combinations of screen printing and plating, yield cell efficiencies of 22.4% and 22.7%, respectively. The more detailed analysis in the following sections reveals that,

"The application of LCO patterning and Ni/Cu/Ag plating enables the creation of ultrafine-line contacts for i-TOPCon solar cells."

even for the hybrid groups, the reduced contact recombination and narrower contact width seem to enable improvements in V_{oc} and J_{sc}. However, these improvements are statistically not significant in this experiment because of the small sample/group size and the wide spread of the results in each group.

The bifacially plated group demonstrates a best cell efficiency of 22.7%. The decreased shading fraction due to the narrow contact width of 25µm leads to increased J_{sc} compared with the process groups with screen-printed front-side contacts.

Reducing contact recombination/enabling thinner TOPCon layer

Since the precursor design for the fabricated solar cells is already optimized for the application of screen-printed contacts, the TOPCon layer thickness is sufficient to prevent metal spiking for screen-printed contacts in the reference group.

Photoluminescence (PL) imaging, shown in Fig. 5, was carried out on the same precursor material to further analyse the contact recombination due to laser-induced damage by the LCO process. A large laser parameter variation was performed with increasing laser power, starting from the threshold power, to properly ablate the SiN_x capping layer. The recombination due to laser damage is observed in the PL image by the darkening of the LCO test fields. The darkened areas are visible on the boron emitter side, independently of the applied laser power. In contrast to that, only a few test fields with large laser powers are darkened on the sample, where LCO was performed on the TOPCon side. This demonstrates that only large laser powers well above the ablation threshold induce contact recombination on this industrially optimized TOPCon layer thickness. Consequently, even lower TOPCon thicknesses would be possible without increasing contact recombination. Similar findings of Haase et al. [19] identified a reduction of the poly-Si thickness down to 75nm to be sufficient for damage-free laser contact openings with UV-ps laser systems. The boron-doped emitter contact recombination increases, as expected, when passivation layers are removed from diffused crystalline silicon surfaces.

Reducing contact resistance

Earlier publications have already demonstrated contact resistivities below 1mΩcm² for plated Ni/Cu/Ag contacts on lightly boron-doped emitters (with surface doping concentration less than $10^{19}cm^{-3}$, R_{sheet} = 140Ω/sq) [20] and n-type TOPCon layers [12]. Random samples of the fabricated i-TOPCon solar cells were further characterized in order to determine the contact resistance. The samples were cut into strips of 1cm, and measured using transmission line measurements (TLMs); the strips were mapped over all the fingers on each strip.

The summarized contact resistance measurements are shown in Fig. 6. The plated contacts feature decreased finger widths down to

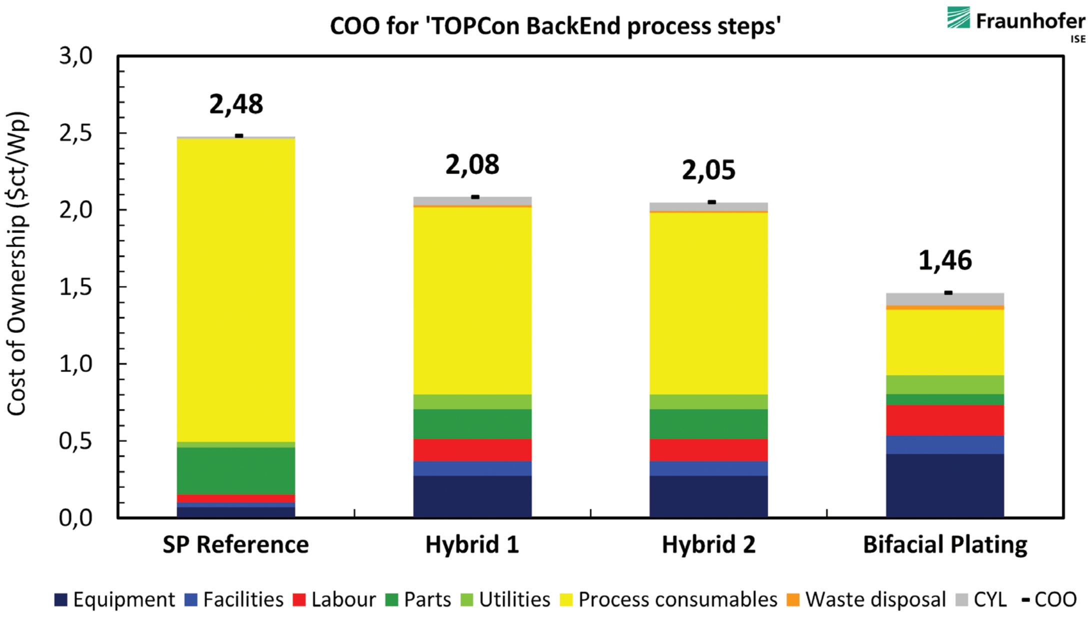

Figure 7. COO calculations for the four back-end process sequences given in Fig. 3.

25μm compared with 40μm for screen printing. For plated contacts, the contact resistance is limited by the Ni–Si interface area, which is defined by the LCO width (18μm). Although the plated fingers have only half the contact/interface width, the measured contact resistance in Fig. 6 is below the values for screen printing for both surface types (boron emitter/TOPCon).

Reducing shading losses by means of highly conductive ultrafine-line contacts

The application of LCO patterning and Ni/Cu/Ag plating enables the creation of ultrafine-line contacts for i-TOPCon solar cells. State-of-the-art mass-production LCO tools allow contact opening widths of 12–18μm, while lab-type tools allow even lower LCO widths, which are below 5μm and limited by the pyramid texture size.

The plating width is scalable by the amount of metal plating. Assuming isotropic growth, the width can be approximated by the LCO width plus twice the plating height. After contact annealing [21], the conductivity of plated Ni/Cu/Ag layers is similar to the conductivity of bulk Cu. Measurements performed on plated Ni/Cu/Ag layers at Fraunhofer ISE show line resistivities of 17.3mΩmm²/m (compared with the value 17.21mΩmm²/m for Cu in the literature [22]). Depending on the interconnection design (number of busbars), these low line resistivities allow finger widths down to 25μm and finger heights of 5μm, without significant limitation by the grid resistance.

Cost calculations

Bifacial grid designs enable further cell efficiency gains for i-TOPCon solar cells. Besides the benefits of bifacial grid designs, however, there are also increased requirements concerning the line conductivity of the rear-side metallization. For both-side screen-printed solar cells, this leads to the need for high Ag lay-down on the front and rear sides. The introduction of plated Ni/Cu/Ag contacts in a bifacial grid design therefore allows material costs to be drastically reduced. In combination with the potential for efficiency gain discussed above, bifacially plated Ni/Cu/Ag metallization for i-TOPCon solar cells may be the most promising approach for metallization.

To evaluate the COO of the back-end processes described in Fig. 3, advanced cost calculations using the SCost modelling approach [23] were performed; these calculations assume TOPCon solar cells with a bifacial grid design. A paste lay-down of 90mg per wafer side (180mg/wafer paste lay-down) is assumed for the screen-printing reference. The front side (boron-doped emitter) and rear side (TOPCon) are metallized with fire-through AgAl and Ag pastes, with assumed Ag content of 88% and 92%, respectively. The paste costs are dominated by the Ag raw material cost, and so other contributions to costs are not significant.

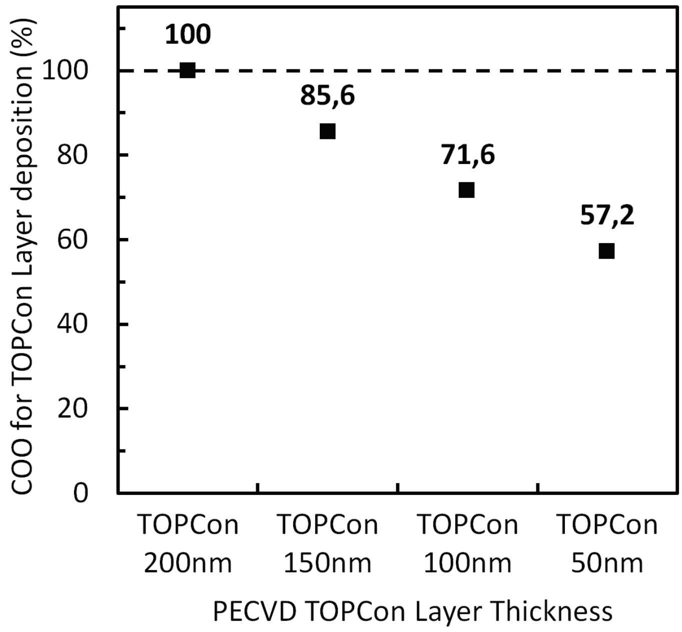

Figure 8. Normalized COO of the PECVD TOPCon process with decreasing TOPCon layer thickness.

"Decreasing the TOPCon layer thickness from 200nm to 50nm can reduce the COO of the TOPCon process by 43%."

The assumptions for the plating equipment are fairly conservative. The lead gained in screen-printing tool development compared with plating is taken into account by the increased investment costs, reduced throughput and higher labour costs for plating. The equipment throughputs are assumed to be 7,200 wafer/h and 5,000 wafer/h for screen printing and plating, respectively. The lower throughput of plating is not based on technological restrictions but on the lack of scaling effects compared with the tool developments in screen printing over the last decade.

Fig. 7 shows the COO ratios for each of the back-end sequences. The COO for bifacial plating indicates a benefit of more than 40% compared with the screen-printing reference. The major cost driver for the screen-printing reference process sequence is the process consumables (yellow) – i.e. the Ag and AgAl pastes. Introducing plating can dramatically decrease the raw material costs. Because of scaling effects over the last decade, the equipment costs for screen printing are significantly lower than those for young technologies, such as plating. With increasing market penetration, however, similar scaling effects are expected for plating.

The hybrid concepts demonstrate a cost benefit of more than 16% compared with the screen-printing reference process. The difference between the two hybrid designs is due to the different

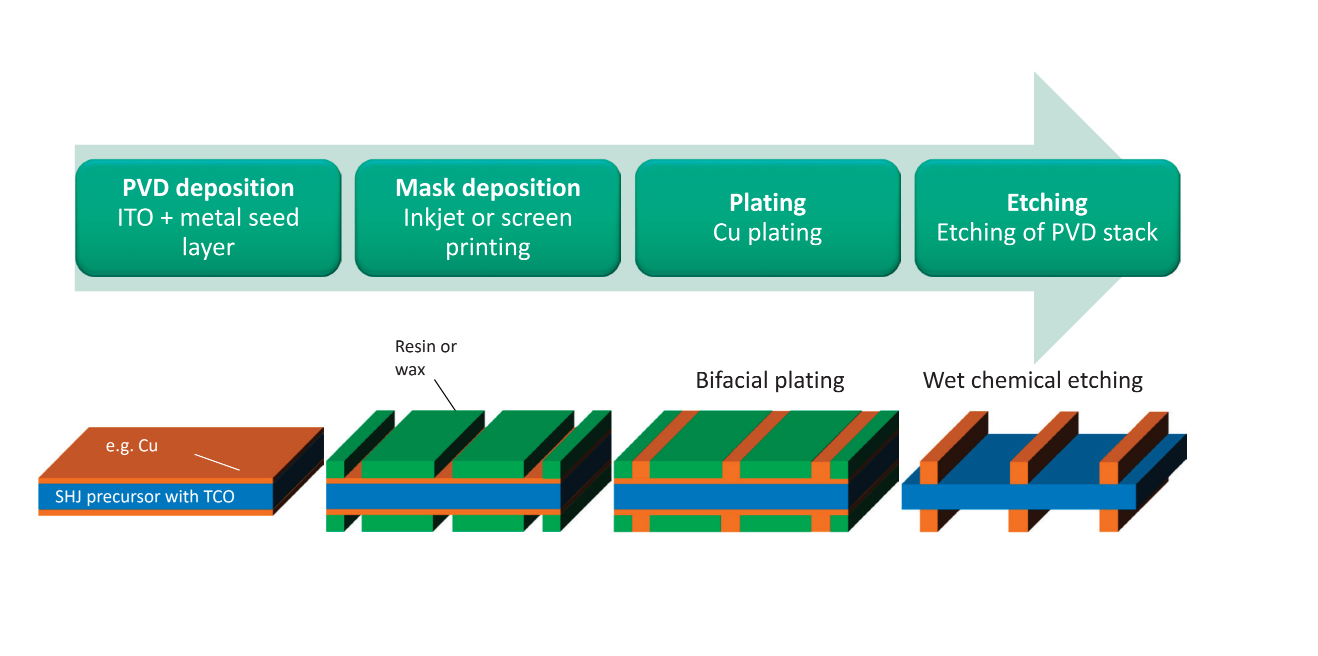

Figure 9. Back-end process sequence for plated SHJ solar cells using organic masking processes.

paste costs in each: Hybrid 1 requires Ag pastes for contacting the TOPCon layer, compared with AgAl pastes for Hybrid 2. Overall, all the back-end sequences involving plating, whether it be hybrid or bifacial, allow drastic cost improvements as a result of lower consumable costs. In the case of an increasing market penetration of plated contacts for TOPCon solar cells, the scaling effects and improvements in throughput will lead to further reductions in equipment costs.

Reducing TOPCon thickness to under 100nm

The implementation of plated Ni/Cu/Ag for contacting TOPCon surfaces has the potential to enable the TOPCon thickness to be decreased without increasing contact recombination. Fig. 8 summarizes the cost calculations for bifacially plated TOPCon solar cells with different TOPCon layer thicknesses in terms of the normalized COO reduction; the figure shows the normalized COO of the TOPCon process for decreasing TOPCon layer thickness. It can be seen that decreasing the TOPCon layer thickness from 200nm to 50nm can reduce the COO of the TOPCon process by 43%.

NOBLE – plated Cu metallization for Si heterojunction solar cells (SHJ)

Plating has always been considered a highly interesting option for metallizing SHJ solar cells. The plating processes fit in very well with the strict constraints of low-temperature processing, as well as offering the possibility of realizing highly conductive Cu grid lines at low material cost. Many research groups (e.g. FhG-ISE, CSEM, ASU, UNSW) and companies (e.g. GS Solar, Sunpreme, Kaneka, Silevo) are carrying out work on plating, while today's largest SHJ solar cell manufacturer, GS Solar, already uses plating in production.

The reason why plating is so interesting for SHJ solar cells is that these cells cannot withstand temperatures above ~250°C. Hence, printing Ag pastes that are cured at a low temperature and with fairly low conductivity need to be used, which results in a high amount of silver being required per cell, especially in a bifacial cell design. The situation becomes even worse when the interconnection of the cells for module fabrication is considered: experience has shown that even greater amounts of silver need to be used to allow soldered interconnection technology. Alternative interconnection technologies, such as SmartWire Connection Technology (SWCT) or the use of electrically conductive adhesives (ECAs), enable the amount of printed silver to be reduced, but incur additional costs in module assembly, as these alternative interconnection technologies are more expensive.

A review of state-of-the-art plating processes for SHJ solar cells was published by Lachowicz et al. in 2018 [24]. The formation of locally plated contacts on transparent conductive oxide (TCO) surfaces requires masking of the non-grid areas; otherwise the entire TCO surface would be plated. Physical vapour deposition (PVD) of metal seed layers feature excellent adhesion on indium tin oxide (ITO) and help to uniformly distribute the plating current, allowing fast simultaneous bifacial plating. Therefore, the most common plating approach, shown schematically in Fig. 9, is:

> "The NOBLE sequence includes PVD metal seed layers for reliable contact adhesion on TCO, and homogeneous plating current distributions."

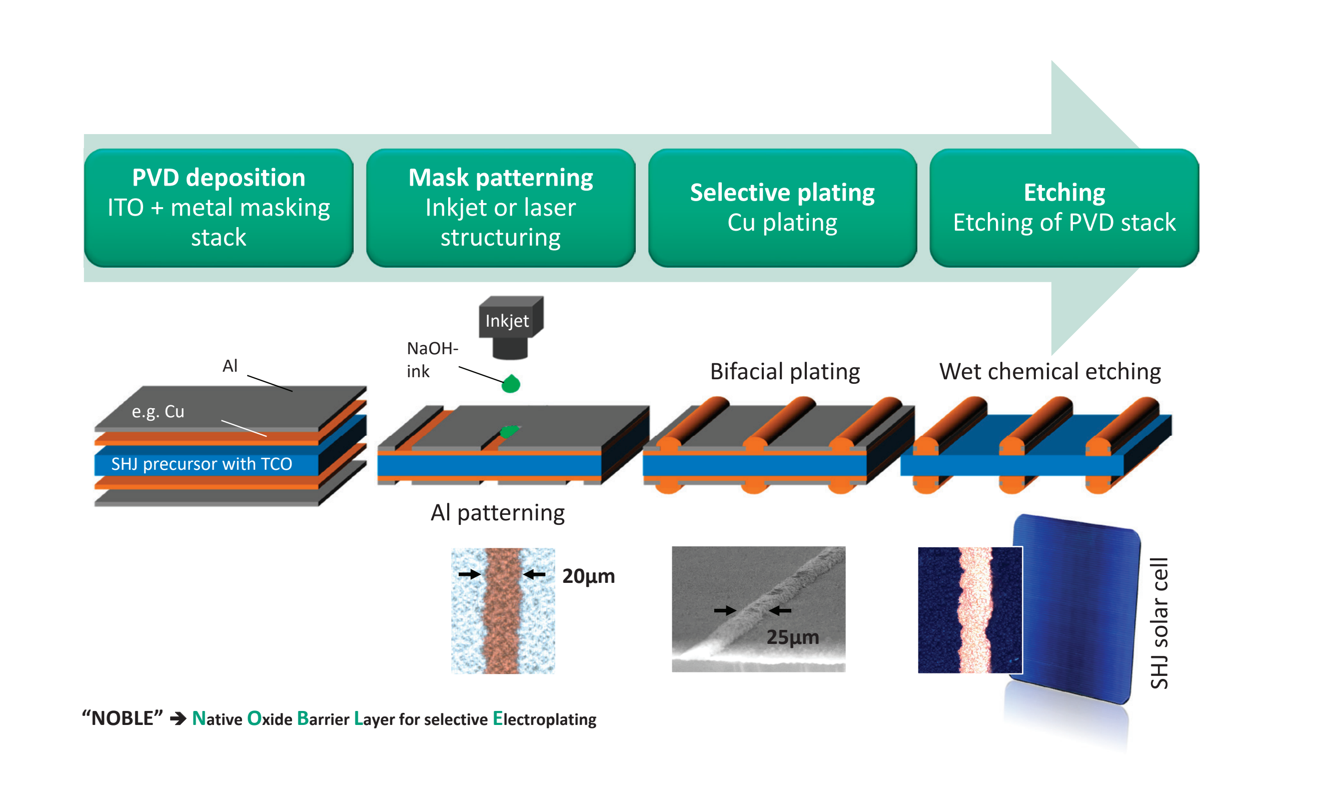

Figure 10. NOBLE process sequence for SHJ solar cells with bifacially plated Cu metallization.

- Deposit a full-area PVD metal seed layer on ITO
- Deposit a structured organic masking layer (e.g. resin or wax)
- Plate the contact grid
- Strip the masking layer
- Etch back the PVD seed layer

This approach is well established in printed circuit board (PCB) manufacturing, where photolithography with dry-film resists is typically used for masking. For solar cell applications, however, inkjet printing is often considered for depositing the mask. The fact that most of the area needs to be covered by the mask (~97%) leads to high consumable costs and lengthy processing times. To reduce consumable costs, a double-print process with a thin masking layer over most of the area, which is thicker close to the openings in the layer, has been introduced [25] and further developed [26]. This masking approach is still found in industrial production, but the treatment of waste water polluted with the organic masking material leads to high costs.

NOBLE process sequence and back-end solutions

At Fraunhofer ISE, the intention is to tackle the cost issues with an organic mask by means of the so-called *NOBLE* process (**n**ative **o**xide **b**arrier **l**ayer for selective **e**lectroplating) [27,28]. The NOBLE sequence includes PVD metal seed layers for reliable contact adhesion on TCO, and homogeneous plating current distributions.

Instead of an organic mask, an Al layer is deposited, which allows the use of the natively grown AlO_x surface in the subsequent plating processes as a non-conductive masking layer. Sandwiched between TCO and Al is a second thin metal layer, which can be freely chosen to optimize the seed layer contact interface properties (contact resistance, contact adhesion). Possible choices for this metal layer include Cu, Ag or Ni. The metal layers can be deposited by PVD in the same tool used for the TCO layers, but with the tool equipped with additional targets. The thickness of the metal layers is in the range 10–100nm.

The Al layer is structured by inkjet printing of alkaline ink [28], laser ablation, or laser-induced forward transfer (LIFT) [29]. The structuring step only requires patterning of the grid area, which is typically about 3% of the wafer surface. The subsequent plating process requires optimized plating electrolytes and reverse pulse plating in order to avoid parasitic plating on the oxidized aluminium surface [30,31]. Both these requirements are compatible, however, with state-of-the-art mass-production inline plating tools. In the final step, the PVD metal layers are chemically etched. The NOBLE process sequence is shown schematically in Fig. 10; all the required tools are available for mass production.

Solar cell integration and contact characteristics

One of the origins of NOBLE lies in the success of solar cells metallized by plating on PVD metal seed

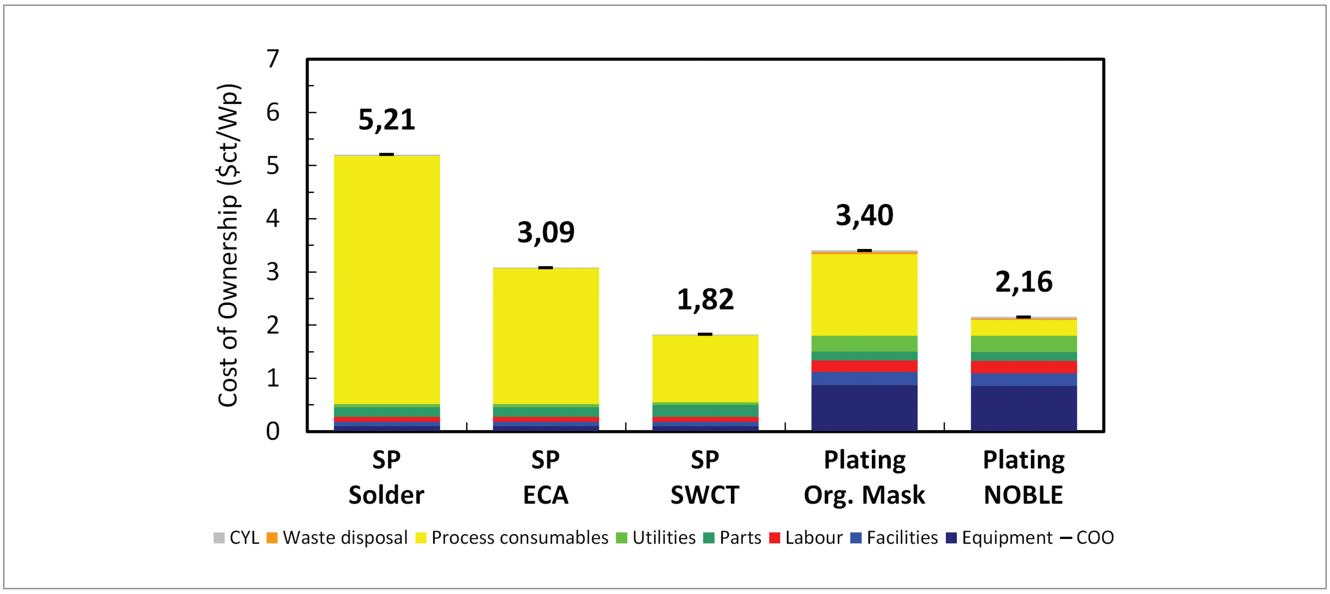

Figure 11. COO calculations for various metallization technologies used for bifacial SHJ solar cells (SP = screen printing). The contributions to the total COO (bold) include consumables and depreciation associated with the metallization processes.

"The integration of Cu-plated contacts can further decrease the production costs of passivated-contact solar cells."

layers masked with an organic resist. Impressive results by CSEM [24] demonstrated solar cell efficiencies η of up to 24.7% with reliable module interconnection using soldering or SmartWire interconnection. There is no reason to believe that with the NOBLE sequence, efficiencies similar to those with an organic mask could not be reached.

The contact resistance is defined by the PVD seed layer and proper interface conditioning before plating. The conductive full-area PVD seed layer allows homogeneous plating current distribution, which in turn enables homogeneous plating height

Interconnection/ Metallization	Printing consumables	Paste or resist lay-down	Printing area (front+rear)
Soldering 5BB Ag screen printing	Low-curing Ag paste	365mg/wafer	11.4%
ECA 5BB Ag screen printing	Low-curing Ag paste	205mg/wafer	8.2%
SWCT Ag screen printing	Low-curing Ag paste	100mg/wafer	4.1%
Soldering 5BB Organic mask	Hotmelt ink	600mg/wafer	7.3%
Soldering 5BB NOBLE (inkjet)	1% NaOH	0.7µl/wafer	7.3%
SWCT NOBLE (inkjet)	1% NaOH	0.7µl/wafer	4.1%

Table 2. Consumables for the printing processes (Ag screen printing and mask patterning) for different metallization and interconnection approaches for SHJ solar cells.

distribution over the entire wafer. The contact geometry for NOBLE is defined by the mask patterning width and isotropic growth around the mask opening.

The first demonstration of selective Cu plating for SHJ metallization was published in 2017 [29]. At that time, the selectivity was achieved by a thin ALD-AlO_x layer and LIFT seed layer patterning. The first monofacial SHJ solar cells created using this process achieved a solar cell efficiency of 22.2%, in comparison to 21.7% for the screen-printed reference solar cell.

In subsequent developments, the focus was on the implementation of a native AlO_x layer as a masking layer, along with inkjet-based patterning processes. The first SHJ solar cells metallized with the printed NOBLE sequence shown in Fig. 10 were published by Hatt et al. in 2019 on small-area [28] and large-area [32] solar cells, achieving cell efficiencies of 20.2% and 20.0%, respectively. More recently, large-area cells with solar cell efficiencies of up to 21.2% were fabricated with the NOBLE back-end sequence. The recent developments were limited by non-optimized mask patterning and PVD seed layer processes. Current process developments are now centring on optimizing these process steps in order to develop the full potential of the NOBLE process for plated SHJ solar cells.

Cost calculations

The COOs for the different back-end approaches are shown in Fig. 11. The COO calculations assume a SHJ solar cell with bifacial grid design, having 120 and 200 fingers on the front and rear sides, respectively. For solder interconnection, five busbars per wafer side are assumed, each with a width of 500µm. The other interconnection scenarios are ECA interconnection and SWCT, both of which do not require any printed metal busbars, which therefore saves on silver. In the case of SWCT, the small wire pitch allows a higher finger resistance with even lower paste lay-down.

The metallization processes are: bifacial Ag screen printing, plating with organic mask, and NOBLE. The assumed Ag paste or resist lay-down for the metallization or mask patterning processes are summarized in Table 2.

In the COO calculations for the metallization sequences shown in Fig. 11, one of the main cost drivers for screen-printing metallization approaches is the metallization consumables. A price of €589/kg was assumed for the Ag printing paste (low-temperature Ag pastes are, however, more expensive). The reduced paste lay-down made possible by using ECA or SWCT results in significant reductions in silver costs.

In terms of cost, plated Cu metallization with or without an organic mask is clearly superior to screen-printed metallization with busbars. The cost of the organic mask, however, is of the same order as the cost of the silver when SWCT interconnection is used. It is here that the NOBLE process has a clear advantage, even when the cost benefit with regard to waste water treatment is not taken into account. Nevertheless, both plating approaches can still be attractive, since interconnection by ECA or SWCT may help to reduce costs for metallization, although typically increasing interconnection costs. The metallization equipment depreciation for the two plating approaches is relatively high as a result of the required add-ons to the PVD tool; however, the depreciation is mostly due to the high investment costs for inkjet printers and plating tools, compared with state-of-the-art screen printers. It can be expected that tool prices will fall, however, if plating is adopted in an increasing number of SHJ production lines.

Conclusion

The integration of Cu-plated contacts can further decrease the production costs of passivated-contact solar cells.

Plating metallization for i-TOPCon solar cells

Bifacial and hybrid (plating/screen printing) TOPCon solar cells with laser-defined and plated Ni/Cu/Ag contacts demonstrate efficiencies of up to 22.7%, and open the way to further reducing the resistive, recombination and optical losses of i-TOPCon solar cells. Low contact resistance and low finger line resistivity allow finger widths less than 25µm, while low contact recombination enables a reduced TOPCon thickness to less than 100nm. Future work will need to focus on estimating the minimum TOPCon thickness that would allow low contact recombination for laser-defined plated Ni/Cu/Ag contacts.

The cost calculations show that the introduction of plated contacts, especially in the form of a bifacially plated grid, enables the back-end processing cost for TOPCon solar cells to be lowered. Further cost savings can be achieved by reducing the TOPCon layer thickness, because of the shallow laser-damage depths associated with ultrashort-pulse laser ablation.

NOBLE Cu-plated contacts for SHJ solar cells

The NOBLE back-end sequence is a low-cost and low-temperature metallization approach for industrial SHJ solar cells. It offers the potential to realize metal grids with excellent electrical performance, suited to reliable module interconnection (e.g. busbar solder interconnection) and low grid resistance for creating high-efficiency bifacial SHJ solar cells.

NOBLE achieves a low COO as a result of the dramatically reduced cost of consumables, independently of the interconnection technology used, with the prospect of further significant cost reductions with regard to equipment and labour. Compared with organic masking, the NOBLE approach avoids organic waste water while decreasing the material costs and amount of patterning consumables.

Acknowledgements

This work was funded by the German Federal Ministry for Economic Affairs and Energy within the frameworks of the Genesis (FKZ: 032474), PV-BAT400 (FKZ: 0324145), TALER (FKZ: 03EE1021B) and C3PO (FKZ: 0324155A) projects.

References

[1] Min, B. et al. 2017, "A roadmap toward 24% efficient PERC solar cells in industrial mass production", *IEEE J. Photovolt.,* Vol. 7, No. 6, pp. 1541–1550.
[2] Feldmann, F. et al. 2014, "Passivated rear contacts for high-efficiency n-type Si solar cells providing high interface passivation quality and excellent transport characteristics", *Sol. Energy Mater. Sol. Cells,* Vol. 120, pp. 270–274.
[3] Verlinden, P.J. 2018, "Moving to terawatt levels of annual solar cell production: Aligning research, technology & production roadmap", TeraWatt 2.0 Worksh., Denver, Colorado, USA.
[4] Bay, N. et al. 2019, "Adaptation of the industrial PERC solar cell process chain to plated Ni/Cu/Ag front contact metallization", *AIP Conf. Proc.,* Vol. 2147, DOI:10.1063/1.5123877.
[5] Horzel, J.T. et al. 2015, "Industrial Si solar cells with Cu-based plated contacts", *IEEE J. Photovolt.*, Vol. 5, No. 6, pp. 1595–1600.
[6] Feldmann, F. et al. 2013, "A passivated rear contact for high-efficiency n-type Si solar cells enabling high V_{oc}'s and FF>82 %", *Proc. 28th EU PVSEC*, Paris, France, pp. 988–992.
[7] Padhamnath, P. et al. 2020, "Development of thin polysilicon layers for application in monoPoly™ cells with screen-printed and fired metallization", *Sol. Energy Mater. Sol. Cells,* Vol. 207, p. 110358, DOI: 10.1016/j.solmat.2019.110358.
[8] Chen, Y. et al. 2019, "Mass production of industrial tunnel oxide passivated contacts (i-TOPCon) silicon solar cells with average efficiency over 23% and modules over 345 W", *Prog. Photovolt: Res. Appl.,* Vol. 41, pp. 1–8.
[9] Chen, D. et al. 2020, "24.58% total area efficiency of screen-printed, large area industrial silicon solar cells with the tunnel oxide passivated contacts (i-TOPCon) design", *Sol. Energy Mater. Sol. Cells,* Vol. 206, p. 110258.
[10] Schultz-Wittmann, O. et al. 2016, "High volume manufacturing of high efficiency crystalline silicon solar cells with shielded metal contacts", *Proc. 32nd EU PVSEC*, Munich, Germany, p. 456–459.
[11] Steinhauser, B. et al. 2018, "Large area TOPCon technology achieving 23.4% efficiency", *Proc. 7th WCPEC*, Waikoloa, Hawaii, USA, pp. 1507–1510.
[12] Grübel, B. et al. 2019, "Plated Ni/Cu/Ag for TOPCon solar cell metallization", *Proc. 36th EU PVSEC*, Marseille, France, pp. 167–171, DOI: 10.4229/EUPVSEC20192019-2BO.2.3.
[13] Büchler, A. 2019, "Interface study on laser-structured plated contacts for silicon solar cells", Dissertation, Albert Ludwig University of Freiburg, DOI: 10.6094/UNIFR/149376.
[14] Shen, X. et al. 2020, "Plated metal adhesion to picosecond laser-ablated silicon solar cells: Influence of surface chemistry and wettability", *Sol. Energy Mater. Sol. Cells*, Vol. 205, 110285.
[15] Arya, V. et al. 2018, "Improvement of solar cell efficiencies for ultrashort-pulse laser contact opening with Ni-Cu plated contacts by optimized LCO-FFO processing order", *Proc. 35th EU PVSEC*, Brussels, Belgium, pp. 805–809.
[16] Mette, A. et al. 2006, "Increasing the efficiency of screen-printed silicon solar cells by light-induced silver plating", *Proc. 4th WCPEC*, Waikoloa, Hawaii, USA, pp. 1056–1059.
[17] Bartsch, J. et al. 2014, "21.8% efficient n-type solar cells with industrially feasible plated metallization", *Energy Procedia,* Vol. 55, pp. 400–409.
[18] Gensowski, K. et al. 2019, "Direct contact

plating-Inline plating solution for ZEBRA IBC by local contacting", *AIP Conf. Proc.*, Vol. 2156, DOI: 10.1063/1.5125876.
[19] Haase, F. et al. 2018, "Laser contact openings for local poly-Si-metal contacts enabling 26.1%-efficient POLO-IBC solar cells", *Sol. Energy Mater. Sol. Cells,* Vol. 186, pp. 184–193.
[20] Feldmann, F. et al. 2017, "Evaluation of TOPCon technology on large area solar cells", *Proc. 33rd EU PVSEC*, Amsterdam, The Netherlands, pp. 1–3.
[21] Song, N. et al. 2017, "Self-annealing behavior and rapid thermal processing of light induced plated copper fingers on silicon solar cells", *Proc. 44th IEEE PVSC*, Washington DC, USA, pp. 1–4.
[22] Lide, D.R. 2005, *CRC Handbook of Chemistry and Physics* [Internet version available online: http://library.aceondo.net/ebooks/Physics/handbook_of_chemistry_and_physics_2005.pdf].
[23] Nold, S. et al. 2012, "Cost modeling of silicon solar cell production innovation along the PV value chain", *Proc. 27th EU PVSEC*, Frankfurt, Germany, DOI: 10.4229/27thEUPVSEC2012-2AV.5.4.
[24] Lachowicz, A. 2018, "Review on plating processes for silicon heterojunction cells" [http://www.metallizationworkshop.info/fileadmin/metallizationworkshop/presentations2019/5.2_Lachowicz_20190530_MIW_ReviewCuPlatingHJTCells.pdf].
[25] Hermans, J. et al. 2014, "Advanced metallization concepts by inkjet printing", *Proc. 29th EU PVSEC*, Amsterdam, The Netherlands, pp. 518–522, DOI: 10.4229/EUPVSEC20142014-2CO.2.3.
[26] Descoeudres, A. et al. 2018, "Low-temperature processes for passivation and metallization of high-efficiency crystalline silicon solar cells", *Sol. Energy*, Vol. 175, pp. 54–59.
[27] Glatthaar, M. et al. 2019, "Method for producing electrical contacts on a component", Patent US 2019 237 599A1.
[28] Hatt, T. et al. 2019, "Native oxide barrier layer for selective electroplated metallization of silicon heterojunction solar cells", *Sol. RRL*, Vol. 41, p. 1900006.
[29] Rodofili, A. et al. 2017, "Laser transfer and firing of NiV seed layer for the metallization of silicon heterojunction solar cells by Cu-plating", *Sol. RRL*, Vol. 1, No. 8, p. 1700085.
[30] Glatthaar, M. et al. 2017, "Novel plating processes for silicon heterojunction solar cell metallization using a structured seed layer", *IEEE J. Photovolt.,* Vol. 7, No. 6, pp. 1569–1573.
[31] Hatt, T. et al. 2018, "Novel mask-less plating metallization route for bifacial silicon heterojunction solar cells", *AIP Conf. Proc.,* Vol. 1999, No. 1, 040009, DOI: 10.1063/1.5049272.
[32] Hatt, T. et al. 2019, "Establishing the 'native oxide barrier layer for selective electroplated' metallization for bifacial silicon heterojunction solar cells", *AIP Conf. Proc.*, Vol. 2147, No. 1, 040005, DOI: 10.1063/1.5123832.

About the Authors

Sven Kluska studied physics at the Albert Ludwig University of Freiburg and received his Diploma degree in 2010, and his Ph.D. in the field of laser chemical processing for silicon solar cells in 2011. His research interests include electrochemical processing for solar cell applications with a focus on plating metallization. He is currently co-head of the Electrochemical Processes group.

Thibaud Hatt studied chemistry at the Joseph Fourier University in Grenoble and at the University of Strasbourg, where he received his master's. He worked on Li-ion batteries at the CEA-LITEN, and then on developing wet-processes for polyamide-imide materials in the fibres industry. He joined Fraunhofer ISE in 2017 as a Ph.D. student to develop electrochemical processes, with a focus on plating metallization on TCOs for silicon heterojunction solar cells.

Benjamin Grübel received his master's in electrical engineering and information technology in 2017 from the Karlsruhe Institute of Technology KIT in Karlsruhe, for which he carried out research on the interfacial oxide layers on laser-structured and plated contacts on silicon solar cells. Currently a Ph.D. student at Fraunhofer ISE in the Electrochemical Processes group, his current field of research is electrochemical metal deposition (plating) on polycrystalline silicon for high-efficiency silicon solar cell applications.

Gisela Cimiotti studied surface and material sciences at the University of Aalen. During her time as senior technologist at RENA GmbH, she was involved in the introduction of the plating technology for silicon solar cell production. Since 2012 she has been working at Fraunhofer ISE in the Electrochemical Processes group, where she focuses on plating.

Christian Schmiga received his Diploma degree in physics from the Georg August University of Göttingen, Germany. Since 2007 he has been with Fraunhofer ISE, where he is project manager for high-efficiency silicon solar cells. His research interests include the evaluation of cell efficiency potentials, the industrial transfer of new solar cell concepts, and the development of cell technologies from lab to line environments, with a focus on n-type cell structures and aluminium alloys.

Varun Arya studied microsystems engineering at the Albert Ludwig University of Freiburg and received his master's in 2016, with a thesis topic of design and fabrication of micro-sized single-mode waveguides made from flexible and non-toxic implantable polymer materials. Since 2017 he has been a doctoral candidate at Fraunhofer ISE, where his current research concerns temporal and spatial laser beam shaping, along with process development for minimal damage ablation of the solar cell dielectric layer for electroplated contacts.

Bernd Steinhauser studied physics at the Albert Ludwig University of Freiburg. In 2017 he received his doctoral degree from the University of Constance on the topic of multifunctional doped passivation layers for solar cell applications. Since 2009 he has been working at Fraunhofer ISE, and is currently a post-doctoral researcher. His research topics include surface passivation, dielectric layer deposition, laser ablation and plating on both p- and n-type silicon solar cells.

Frank Feldmann studied electrical engineering and information technology at the Technical University of Aachen (RWTH) in Germany from 2005 to 2010. In 2015 he received a Ph.D. from the Albert Ludwig University of Freiburg for his work on the TOPCon technology. He is currently is a post-doctoral researcher at Fraunhofer ISE.

Jonas Bartsch studied chemical engineering at the University of Karlsruhe and received his Diploma degree in 2007. He joined Fraunhofer ISE to pursue a Ph.D. in the field of advanced front contacts for silicon solar cells with plating technology. After receiving his Ph.D. from the Albert Ludwig University of Freiburg in 2011, he continued to work with plating at Fraunhofer ISE and is currently co-head of the Electrochemical Processes group.

Baljeet Singh Goraya studied renewable energy engineering and management at the Albert Ludwig University of Freiburg, and received his M.Sc. in 2016. He has since worked at IPVF, France, and rejoined Fraunhofer ISE in 2019. His current field of research is technology assessment and techno-economic evaluation, with a focus on PV manufacturing cost calculations, technology transfer and road-mapping activities for both established and emerging PV technologies.

Sebastian Nold studied industrial engineering at the University of Karlsruhe, Germany, and the University of Dunedin, New Zealand. He received his Diploma degree in industrial engineering from Karlsruhe in 2009, and his Ph.D. from the Albert Ludwig University of Freiburg in 2018. He has been with Fraunhofer ISE since 2008, working in the fields of cost modelling, technology assessment and techno-economic evaluation of silicon PV production technologies.

Andreas Brand studied physics and laser technology at RWTH Aachen, Germany. He has many years of experience in ultrashort pulse lasers and their applications from his time at the Fraunhofer Institute for Lasertechnology in Aachen. In 2011 he joined Fraunhofer ISE to pursue a Ph.D. in the field of laser micro-machining of thin layers on semiconductors. He has been the head of the Laser Process Development team since 2017.

Jan Frederik Nekarda studied physics at the Ludwig Maximilian University of Munich and the Albert Ludwig University of Freiburg. He joined Fraunhofer ISE in 2005 and received a Ph.D. from the University of Constance in 2012. Since 2018 he has been the head of the PV Production Technology – Structuring and Metallization department.

Markus Glatthaar received his Ph.D. in physics in 2007 from the University of Freiburg. After his Ph.D. studies in organic solar, he worked as a postdoc at Fraunhofer ISE in the field of crystalline silicon solar cell characterization. Since 2012 he has headed the Advanced Development for High Efficiency Silicon Solar Cells department at Fraunhofer ISE.

Stefan W. Glunz received his Ph.D. from the University of Freiburg in 1995. He is the director of the Photovoltaics – Research division at Fraunhofer ISE and professor for Photovoltaic Energy Conversion at the Albert Ludwig University of Freiburg. His research interests include the design, fabrication and analysis of high-efficiency solar cells.

Enquiries
Sven Kluska
Tel: +49 761 4588-5382
Email: sven.kluska@ise.fraunhofer.de