Current trends in c-Si PV front-side metallization

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ABSTRACT

Despite considerable progress in screen-printing processes for crystalline silicon solar cell metallization, alternatives are still of interest because of their potential cost and performance advantages. Plating processes are one alternative that can be either combined with printed seed layers or used for full front-contact deposition. Although there are advantages to both approaches, there are also challenges that must be faced. Plating nickel and copper onto printed seed layers is very simple and involves only minor process modifications. With regard to undesired paste–electrolyte interaction, noticeable progress has been made during the past few months, bringing this process closer to industrial implementation. Plating nickel directly onto silicon offers the possibility of contacting emitters even with a surface-doping concentration as low as $8\times10^{18}\text{cm}^{-3}$, while achieving similar performance to that of an evaporated contact metallization. To obtain sufficient adhesion, an in-depth understanding of the interface processes during silicidation is necessary. Gaining this understanding has enabled high peel forces greater than 2N/mm to be realized using a standard solder-and-peel procedure at a 90-degree angle. Process simplification will make such a process highly attractive for solar cell metallization, which is all the more important, as high-efficiency concepts are appearing that require advanced metallization schemes.

Introduction

Getting ahead of screen printing for front-side metallization of industrial crystalline silicon solar cells is a moving target for alternative technologies. Screen-printing contact qualities have been achieved which a couple of years ago seemed to be unattainable for this technology. While novel approaches – such as metal inkjet printing [1], seed printing and plating [2], dispensing [3] and laser transfer contacting [4] – have been intensively discussed and have repeatedly demonstrated their technological potential to realize high-quality solar cell contacts, no cell manufacturer has so far been able to transfer any of these approaches to industrial production.

Paste reduction in front-side metallization

One of the factors influencing the development of contact technology is of course the currently very strained economic situation. Lately, there has not been capital to buy machines, and efforts to implement new processes have been made difficult. Instead, it has been easier to simply decrease the amount of paste needed per cell for front-side metallization. During the last two years, this quantity has been reduced from over 200mg per cell to the current amount of close to 100mg per cell. Fig. 1 shows the reported amounts of paste used per cell on the front side, taken from various publications over the last two years, together with an estimate of typical amounts used by technological leaders and mass producers in industry. This development is a consequence of the two strong drivers for PV cell manufacturers, namely the higher price of silver and the strong fall in module prices that has dominated the PV sector since 2009.

The decreasing trend in wet paste lay-down is a result of the combination of material improvements, printing process enhancements and cell process adjustments. The latest screen-printing paste generations yield quite dense silver layers and allow the printing of fine lines with a high aspect ratio, while offering improved capability for contacting high-performance emitters with low surface doping concentration [5]. At the cell level, emitters have been modified to provide high voltage potential while still meeting paste requirements [6]. Changes in busbar design have already been implemented by some manufacturers in order to further reduce recombination losses and paste consumption.

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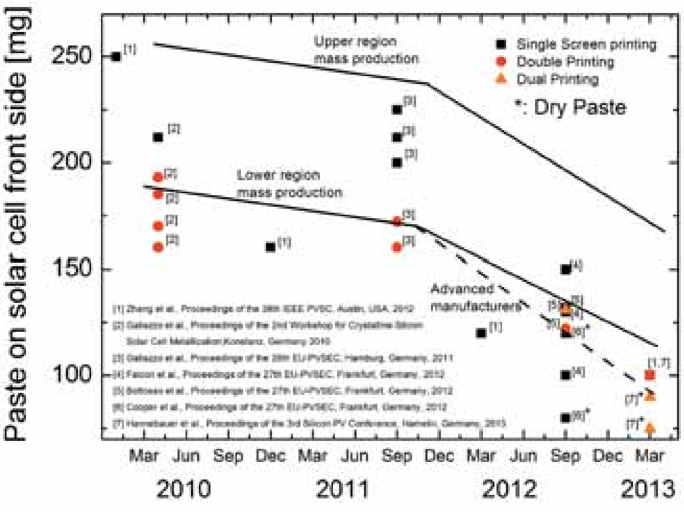

Figure 1. Development of wet paste lay-down for screen-printed front-side metallization of crystalline silicon solar cells 2010–2013. (Note: references given in the graph do not correspond to those in the Reference section of this paper.)

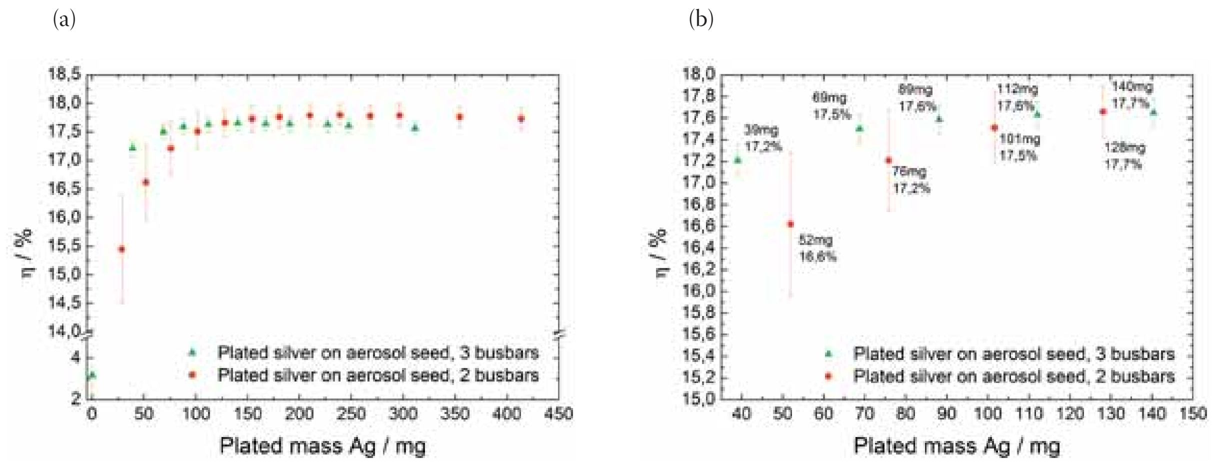

Figure 2. Dependency of cell efficiency on the mass of conductive material on the front surface, studied for the example of plated silver on top of a very thin aerosol seed layer [8]: (a) overview; (b) close-up of the region of strong influence.

Of course, at some point the laws of physics will dictate that a certain amount of material be present on the cell to allow the current to be transported without considerable power losses occurring. For today's industrial three-busbar solar cells with low paste lay-down (see Fig. 1), this point is no longer far off. The number of busbars plays a significant role in these calculations, and multi-busbar or wire electrode concepts can help to further reduce the required amount of silver [7]. The transition from two busbars to three has been a key factor in enabling the paste reductions described above.

Fig. 2 shows the evolution of the efficiency of solar cells with aerosol-printed seed layers (~4mg of silver in the seed layer for a 156 × 156mm^2 solar cell), reinforced by homogeneous, dense and highly conductive plated silver. Different trends can be derived from this investigation [8]. Generally, the two-busbar concept allows a slightly higher efficiency at the cell level; however, because of the longer contact fingers, more material is needed for that configuration. On the other hand, the three-busbar concept is more tolerant of smaller contact cross sections. Both concepts begin to lose efficiency if too little conductive material is present on the cell. Below a certain level, which depends on the metallization technology, the drop becomes very rapid, and process stability becomes critical. The close-up in Fig. 2 shows that after this point has already been reached, paste reduction is achieved, at least to some extent, at the cost of a decrease in efficiency. Less paste lay-down may lead to finer contact fingers and higher cell currents, but this can no longer compensate fill factor losses after a certain point. What this means in terms of yearly yield difference is dependent on the operation site of the module.

Idealized simulations with Fraunhofer ISE's tool GridSim 2D [9] indicate that a hypothetical, perfectly homogeneous and well-conductive screen-printed grid for an Al-BSF cell with a 90Ω/sq emitter and an efficiency potential of about 19% needs around 80mg of paste to reach maximum cell efficiency. The integration of processing and material costs into this tool has allowed the evaluation of not only the technological optimum for a grid layout, but also the economic optimum (minimum cost per W_p at the module level). Under the same assumptions, the economic optimum lies at ~60mg paste per cell, which already takes into account a reduced busbar coverage.

Replacements for silver

While the trend shows that considerable reductions in silver consumption have been possible by advanced screen printing, the question of material costs and availability remains open when considering the perspectives of PV. Technological improvements and scaling effects in mass production only allow, in the best case, a reduction in production costs as far as the material costs. Eventually, the material costs will be the dominant remaining cost factor at the end of the learning curve. At this point, silver will be one important obstacle to further cost reduction, which is especially true if the growth in PV production significantly increases the global demand for silver.

Since a replacement for silver is very difficult to realize with screen-printed and fired contacts (owing to the highly distinctive combination of the properties of silver – nobility, low melting point, high conductivity, etc.), various alternatives to screen printing are being explored. One of these is plating technology, which is under intensive investigation at various research institutions, such as the University of New South Wales in Australia, imec in Belgium and Fraunhofer ISE in Germany. Plating is a widely used industrial process in other fields, for example in microelectronics. In PV, plated nickel-copper contacts have already been successfully implemented by BP for the production of their Saturn cell [10].

Plating

The advantages of plating are its ability to deposit perfectly dense, highly conductive layers of multiple materials, at a very low temperature, at a relatively high speed and at low cost. Two process options for masking the plating process to form the grid on the front side of the solar cell are of particular interest: 1) plating on a thin, printed and fired silver seed layer; and 2) laser structuring of the anti-reflective coating and subsequent plating directly on silicon. As plated materials, nickel and copper are the most interesting combination: nickel is able to form an excellent contact to silicon and prevents copper diffusion, while copper is highly conductive and serves as the main current-carrying layer.

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Plating on printed seed layers

Plating on a printed layer can act as a bridging technology, since existing production lines can be retrofitted by adding just the plating tools. Compatibility with printing technology is a major advantage of this approach, as all the above-mentioned progress in printing technology can be exploited. Besides

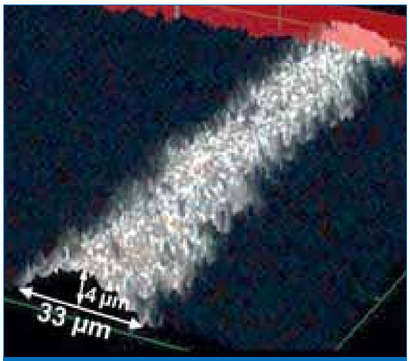

Figure 3. Results of fine-line screen printing to enable subsequent plating, achieved at Fraunhofer ISE [14].

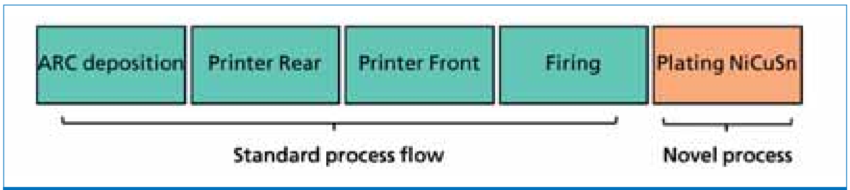

Figure 4. Back-end process flow for the seed and plate approach, which uses printed seed layers and reinforcement with nickel-copper plating. The standard back-end is shown in green, and the additional process in orange.

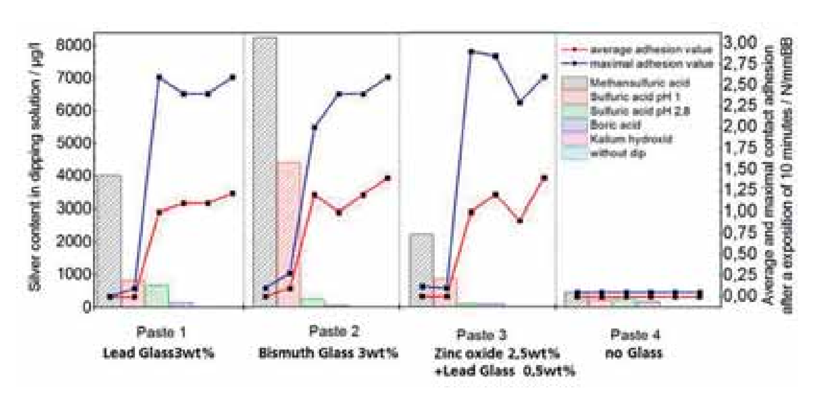

Figure 5. Peel force results for dipped solar cells after exposure to electrolyte chemicals. The bar chart shows the corresponding amount of silver dissolved from the glass into the dipping solution, evaluated by ICP-OES [15].

saving silver, the contact resistance between the silicon and the metal contact is significantly reduced by a combination of printing and plating [11]. While novel printing techniques – such as aerosol printing [12], inkjet printing [1] and high-throughput flexographic printing [13] – offer the highest potential here, the best choice in the current economic situation is to rely on screen printing, as the technique is already available in standard production lines. The latest results at Fraunhofer ISE show that it is possible not only to print very narrow lines with a few simple process adjustments [14] (Figs. 3 and 4), but also to achieve lay-downs as low as 20mg of paste per cell (156 × 156mm^2). When customized pastes with reduced silver content are used, costs can be further reduced by following this strategy.

While contact adhesion issues because of electrolyte influences on the paste have been a major concern in the past, recent results have shown that this can be remedied by simple process modifications [15]. One major influence is the pH of the electrolyte solutions used. The impact on adhesion is stronger when the plating chemistry used is more acidic. This is

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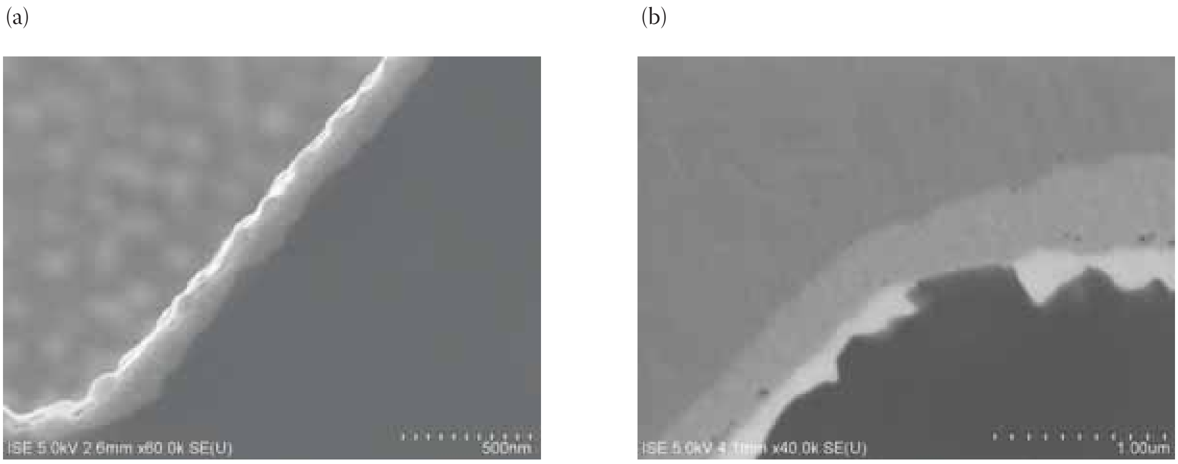

Figure 6. A study of the silicon–nickel silicide–nickel–copper interface: (a) cross-sectional view of a thin silicide layer formed in a single-step process – the formation depth can be accurately controlled by the thermal budget; (b): cross section of the full stack.

linked to dissolution reactions of typical compounds contained in the glass frit that are responsible for the adhesion of the printed seed layer, as shown in Fig. 5. If a low-acidity copper electrolyte is used, part of the problem is solved. For nickel plating, it is not sufficient to increase the pH of the bath. Higher plating rates and reduced process temperatures lead to improved adhesion for this process. Even more importantly, chlorides typically contained in nickel electrolytes strongly etch the oxidized silver layer between the glass frit and the silver bulk – a layer that is crucial for adhesion [16]. The use of chloride-free electrolytes yields similar nickel layer properties and provides the adhesion needed for module integration.

Direct plating

For directly plated contacts, metal–silicon adhesion has also been a major concern, hindering the adoption of this method. The reasons for the observed low adherence have so far not been entirely clarified. However, recent studies at Fraunhofer ISE have led to an improved in-depth understanding of the interface situation between plated metal and silicon [17]. In particular, the role of silicides, the conditions for their formation and the positive effects on adhesion are better understood. On the basis of these investigations, a two-stage process for contact formation has been developed, featuring etchback of unreacted nickel and replating. This process solves the adhesion issue that had existed until now. Two examples of typical interface situations, taken from the microcharacterization study, are shown in Fig. 6. High peel forces were repeatedly demonstrated (Fig. 7), indicating superior stability for this type of contact. Such two-step processes are known from the microelectronics industry [18] and, presumably, have also been used by BP solar [19].

Transferring the technique to solar applications demands that the processing steps involved be reduced. It is currently Fraunhofer ISE's key objective to simplify this relatively complex process sequence. Fast laser processing for ARC structuring and removal of etchback steps by full nickel consumption upon silicidation are among the first topics to be addressed. In addition, recent results indicate that much cheaper and faster light-induced plating (LIP) technology can be used to create such contacts instead of electroless plating for seed layer formation. Some simplifications, for example thermal contact formation after full stack plating, have already been studied, and promising results have been achieved [20]. After these features are implemented in the process sequence, a high compatibility with industrial needs will be achieved.

The efficiency potential of the direct plating process is even higher than that of plating on printed seed layers, as has impressively been demonstrated very recently by Schott Solar: an independently confirmed efficiency of 21.3% was obtained with an industrial-

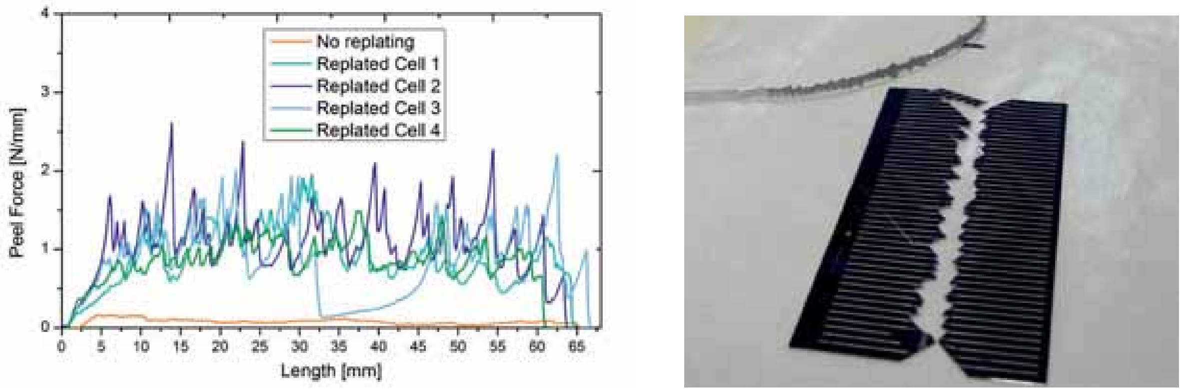

Figure 7. Peel force diagram of the contact system created by direct nickel plating onto silicon, followed by copper and silver plating. Standard cell connectors were soldered onto the busbars in an industrially typical process. Because of the progress in understanding the interface processes between nickel and silicon, it has been possible to develop a pre-treatment sequence that permits very high peel forces, even at 90-degree peel angles as shown in this graph.

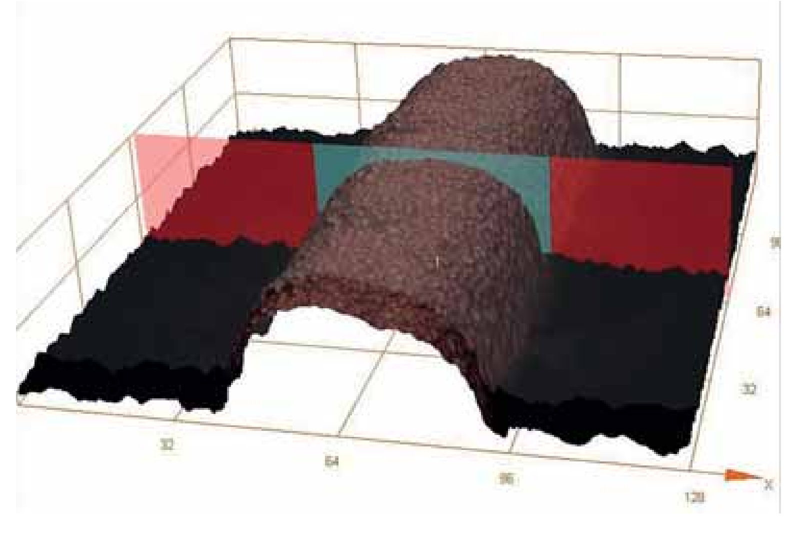

Figure 8. Example of a contact finger created by laser ablation and direct nickel-copper plating (contact width = 45µm and contact height = 22µm).

size p-type Cz PERC solar cell using this contacting system [21]. A yet further improved emitter with low surface doping concentration would allow the open-circuit voltage (V_{oc}) of such a cell to be boosted from the reported 662mV to 680mV, bringing the efficiency into the region of 22%. At Fraunhofer ISE, the ability to contact an emitter with a surface doping concentration of 8×10^{18} using plating technology has been successfully demonstrated, leading to a V_{oc} of up to 679mV [14]. The results match those of an evaporated titanium/palladium/silver stack. When such a homogeneous emitter is used, loss-free contacting can only be achieved using alternative approaches.

Depending on the type of ARC structuring technology, a plated contact will additionally offer the advantage that the entire area underneath the contact contributes to the transfer of current between metal and semiconductor. This makes it suitable for all kinds of metallization application. Very narrow contacts of down to 20µm can be created by laser structuring, simultaneously achieving high aspect ratios of about 1:2 (height:width), as copper electrolytes may be customized to plate upwards rather than sideways (Fig. 8). The optical width of such semi-roundish contacts is considerably lower – down to 20µm. The maturing of this technology will be greatly accelerated by the recent achievements mentioned above.

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Plating vs. screen printing

From an economic point of view, the two plating technologies have been benchmarked against an assumed very advanced screen-printing process (Fig. 9). The results indicate that the savings potential is not as attractive as two years ago, when silver consumption on the front surface was still considerably higher (Fig. 1), but the economic advantages are still striking. Moreover, the plating processes discussed above have not been fully

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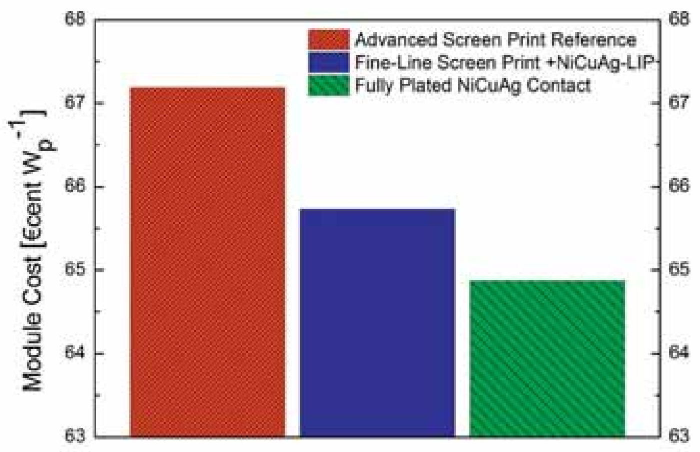

Figure 9. Comparison of the metallization costs for an advanced screen-printing process (cf. Fig. 1) with the two alternative approaches, featuring plating on printed seed layers and direct plating on laser-structured ARC. The calculations take into account machine costs, labour costs, depreciation, all infrastructure costs, waste treatment and so forth. Silver material costs were assumed to be €1000/kg.

optimized yet in terms of performance and cost. The scope for optimization of the plating processes, as offered in an industrial production environment, suggests a potential for further reductions in cost. If just the material costs are taken into account, which represents an idealized situation at the end of the learning curve, the savings potential is by far higher.

> “The scope for optimization of the plating processes suggests a potential for further reductions in cost.”

Further perspectives and conclusion

In the light of the current developments in the PV industry it seems that, up until now, technological pioneers have profited more from such advanced metallization technologies than producers of standard cells. Tetrasun have reported an impressive 21.0% (125 × 125mm^2) with a process of plated copper on a seed layer [22], although the nature of the layer is not entirely clear. Kaneka have very recently reported 23.5% on a 156 × 156mm^2 heterojunction solar cell with electroplated copper contacts, profiting from the high conductivity of the plated layer and the low process temperatures [23]. And, of course, SunPower is using plated copper as the conduction layer for the contacts of all their back-contact back-junction solar cells. The recent progress in plating technology for solar cell metallization described in this paper will make this approach accessible to all PV manufacturers, and not just to the technological leaders.

As the journey towards high efficiencies is ongoing and this path is also opened for mass producers, novel metallization concepts will again be the focus of attention in high-volume crystalline silicon solar cell production too.

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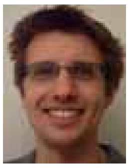
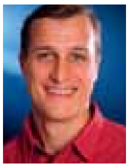
About the Authors



Dr. Jonas Bartsch joined Fraunhofer ISE in 2007, working on electrochemical techniques for advanced solar cell front-side metallization. He received his Ph.D. degree from the University of Freiburg in 2011 in the same field. Since then, Jonas has continued researching plated solar cell contacts as head of the Plating Process Technology team at Fraunhofer ISE.

Dr. Markus Glatthaar received his Ph.D. in the field of organic solar cells from the Albert Ludwig University of Freiburg, Germany, in 2007. From 2008 to 2010 he held a postdoctoral position at the Fraunhofer ISE, where he worked on the characterization of silicon solar cells, mainly focusing on photoluminescence imaging methods. In 2011 he was a senior solar cell technologist at RENA GmbH. Since 2012 Markus has been head of the Novel Processes department within the Solar Cells – Development and Characterization division of ISE.



Achim Kraft studied electrical engineering at the University of Applied Science in Hanover. He received his master's degree in renewable energies from the University of Applied Science in Berlin, before joining Fraunhofer ISE as a Ph.D. student in January 2012. Achim is a member of the Plating Process Technology team, working on plated copper front-side metallization techniques for silicon solar cells. His research focuses on the interaction between electrolytes and printed contacts during the plating process.

Andrew Mondon studied crystallography and materials science in Freiburg, graduating with a diploma in 2010. The work for his diploma thesis was carried out at Fraunhofer ISE, where he has been working on electrochemical solar cell metallization since 2009. In June 2012 Andrew began working on his Ph.D., the topic of which is direct nickel copper metallization for crystalline silicon solar cells, with a particular focus on nickel silicide formation.

Andreas Lorenz studied printing technology at the University of Printing and Media in Stuttgart and graduated in 2006. From 2006 to 2012 he worked at manroland AG, Offenbach, as a research engineer and junior product manager for colour control systems. Since 2012 Andreas has been working as a Ph.D. student at Fraunhofer ISE in the field of printing techniques for solar cell metallization.

Laura Sutor received her B.Sc. in business and engineering from the Karlsruhe Institute of Technology in 2013, where she focused on the cost and effectiveness of copper metallization for solar cells. Laura is currently working towards her master's degree in business and engineering at the same institute, and is also at the Fraunhofer ISE in Freiburg.

Sebastian Nold studied industrial engineering at the University of Karlsruhe, Germany, and the University of Dunedin, New Zealand, and earned his diploma in industrial engineering at Karlsruhe in 2009. He has worked at the Fraunhofer ISE since 2008 in the field of cost calculation, technology assessment and economic evaluation of new concepts in the production of silicon solar cells. Sebastian is currently completing his doctoral thesis at the ISE on the economic assessment of silicon solar cell production along the PV value chain.

Dr. Stefan W. Glunz is the director of the Solar Cells – Development and Characterization division at Fraunhofer ISE. He received his Ph.D. degree in 1995 from the University of Freiburg, and his research focuses on the design, fabrication and analysis of high-efficiency silicon solar cells. Among other scientific and technological achievements, Stefan's group has set the current efficiency world record for solar cells on multicrystalline silicon.

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