Simple and reliable processes for creating fully plated nickel–copper contacts

Jonas Bartsch, **Andreas Brand**, **Dirk Eberlein**, **Andrew Mondon**, **Carola Völker**, **Marco Tranitz**, **Martin Graf**, **Jan Nekarda**, **Ulrich Eitner**, **Daniel Philipp** & **Markus Glatthaar**, Fraunhofer Institute for Solar Energy Systems ISE, Freiburg, Germany

ABSTRACT

This paper presents the first 60-cell module results from a very simple process scheme for creating fully plated nickel–copper contacts on crystalline silicon solar cells. Standard Cz back-surface field (BSF) cells are processed in a completely analogous way to the standard process sequence up to and including rear-side screen printing. After a firing step for BSF formation, the front-grid positions are defined by picosecond pulse laser ablation and plated with nickel, copper and silver; this is followed by a short thermal anneal. Cell classification produces a very neat efficiency distribution of 19.6±0.1%. Solder and peel testing shows this approach to be competitive with standard screen-printed contacts in terms of adhesion. A batch of 60-cell modules were fabricated from the cells in a standard automated tabber–stringer system and subjected to thermal cycling and damp heat testing as part of the IEC 61215 reliability test sequence. The modules passed the test sequence without showing any signs of electrical degradation caused by, for example, copper diffusion.

Introduction

The silver paste conductor grid on a traditional silicon PV cell contributes approximately 18% to the cell's cost. For this reason, industry roadmaps call for the use of an alternative to silver paste by 2018 in order to render PV the most economical choice for electricity production [1].

Direct nickel–silicon contacts offer many advantages and prospects for the metallization of current and future solar cell concepts. The nickel–silicon contact resistance is lower than that of printed silver contacts; moreover, nickel allows the use of copper as a conducting layer, since it effectively hinders the diffusion of copper into the silicon bulk. The cost of raw materials is considerably lower for plated metallization (even at the currently low price of silver), and process costs can be expected to decrease even more as this technology enters the market. An example of the resulting contact system is shown in Fig. 1.

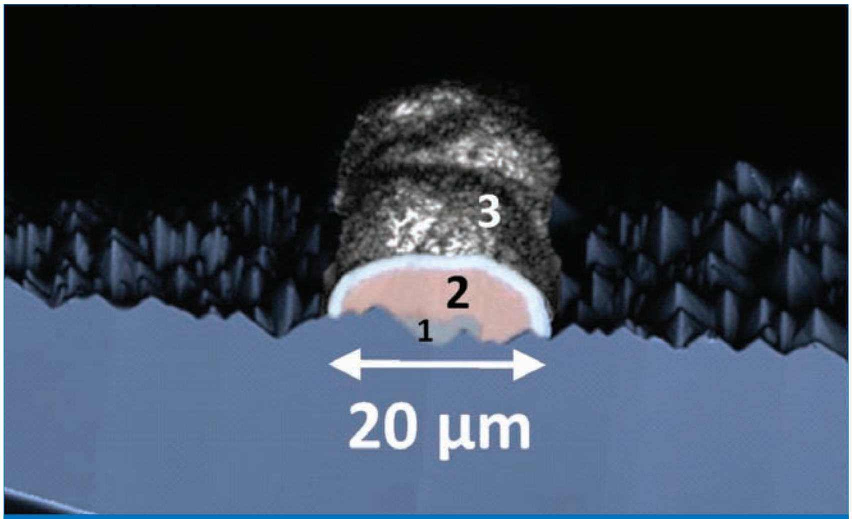

Figure 1. Microscopic image of the cross section of a directly plated nickel–copper contact; in this case the seed layer is ~5µm wide, resulting in a total contact width of 20µm. Nickel (1) is directly deposited onto silicon in regions removed by laser scribing. Copper (2) is plated on top of the nickel, producing a dense layer with very high conductivity. Silver (3) (or tin) is used to protect the contact against corrosion and to promote solderability. Adjacent to the nickel diffusion barrier layer, direct copper–silicon contact is prevented by the SiN_x ARC.

> "Direct nickel–silicon contacts offer many advantages and prospects for the metallization of current and future solar cell concepts."

The plating process is also very attractive for future cell designs. In cell concepts where the rear side is no longer the limiting factor (e.g. PERC solar cells), it has been shown that plated metallization approaches allow considerable efficiency advantages [2,3]. This is supported by new innovations in laser structuring techniques [4] that may allow feature sizes of as little as 5µm in the future, resulting in a geometrical finger width of ~15–20µm and an optical finger width less than 10µm [5] (cf. 40µm in Fig. 2). PERC cell concepts will approach 22% efficiency, or even surpass this mark, using a plated metallization. The first promising steps in this direction have already been made using standard rear passivation schemes with Al_2O_3 and SiN_x [2,3], or using p-type PassDop [6]. With the use of plated NiCu metallization (H-pattern cells) on 156mm × 156mm PERC cells provided by Roth & Rau, the latest results at Fraunhofer ISE have demonstrated up to 21.1% efficiency. In addition to low-cost front copper contacts, these cells featured a low-cost rear Al foil metallization [7].

A further development step in PV with the aim of achieving higher efficiencies may well be the transition to n-type base material. Here the task of contacting boron emitters is accomplished very well with the use of nickel [8], whereas silver–aluminium pastes still suffer from V_{oc} losses due to Al-induced spiking [9,10].

With n-type material, there is some industrial focus on very advanced cell concepts that are easily scalable in principle, but have very high requirements in terms of metallization (e.g. n-type PassDop [11] or TopCon [12]). The n-type PassDop cell concept has already demonstrated cell efficiencies of above 23% [13], while the TopCon design recently demonstrated 24.4% efficiency [14], with the potential of reaching over 25%. Even though the passivation layers that yield the highest efficiency can be deposited using simple 1D processes, their temperature stability is critical, which prohibits the use of standard screen printing as the metallization technique.

Such cell concepts profit immensely from a plated metallization that is technologically close to an evaporated metallization approach, as used in CMOS technology and for the highest-efficiency achieving laboratory solar cells. However, in contrast to the clean-room model process, costly structuring and vacuum metal deposition processes can be replaced by simple and cheap laser and plating processes, making the approach suitable for industrial solar cell manufacturing.

Historically, nickel plating for solar cell metallization has been employed by several groups and industrial players, the most prominent being BP Solar (Saturn cell) [15] and SunTech (PLUTO cell) [16]. While the former uses a process sequence that, although expensive, works well, the latter uses cheap and simple techniques. However, despite excellent cell results, large-scale implementation has not yet been realized. One possible explanation for this is the low contact adhesion that has been observed for plated contacts in the past.

Accordingly, both process complexity and metal–silicon contact adhesion need to be considered in current developments to enable chances for industrial success. The work reported in this paper demonstrates that a simple process route can fulfil the requirements in terms of both adhesion and electrical cell parameters.

Experimental

In this study more than 600 precursor cells without front-side metallization provided by an industrial partner were contacted with a plated front-side metallization. It must be stressed that the cells were entirely pre-processed on an automated production line that was fully optimized with regard to the requirements of a screen-printed front-side metallization. This shows that the process is more or less directly implementable in accordance with a given production standard. The state of the precursors before plating was: diffused $POCl_3$ emitter, random pyramid texture, SiN_x ARC and printed and fired rear-side metallization (Al BSF and silver pads). The 65Ω/sq. emitter selected for this demonstration

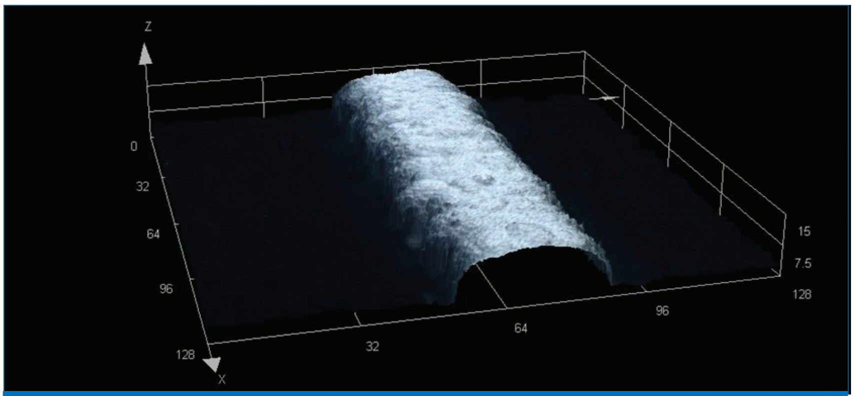

Figure 2. 3D microscope image of the contact fingers achieved for this batch using a non-optimized laser process.

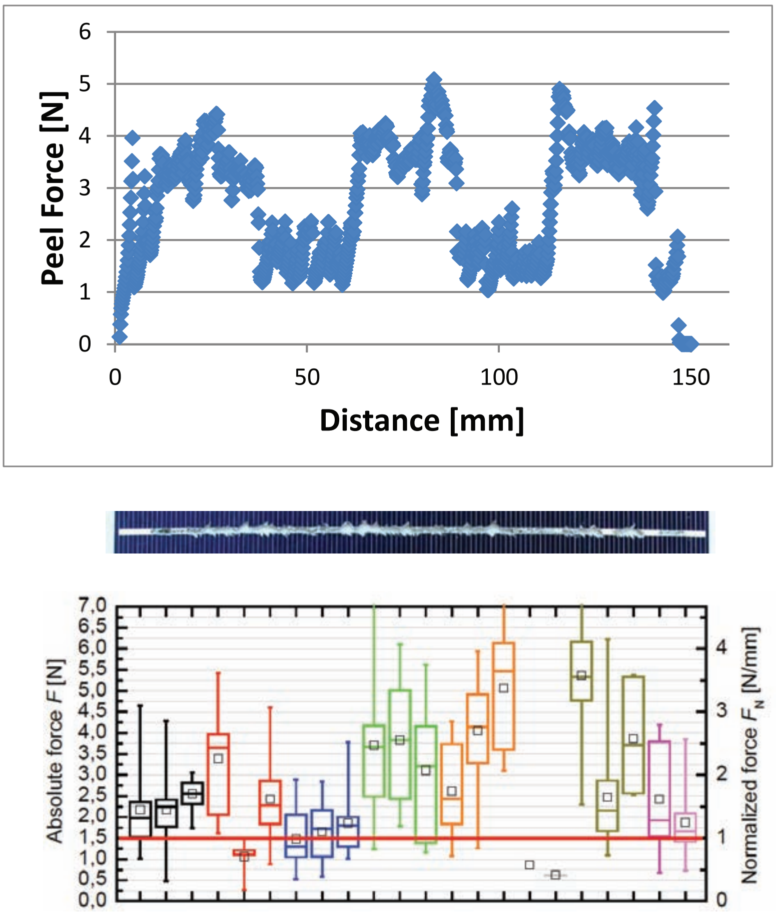

Figure 3. Top: typical peel force diagram obtained for plated cells. Middle: the corresponding failure mode is cell breakage at high forces. Bottom: statistical evaluation of peel forces for different soldering processes (represented by different colours), with simultaneous soldering of the front and rear sides. Highest peak values of peel forces are greater than 7N. Note: low adhesion values relate to the adhesion of the ribbon between soldered attachment points.

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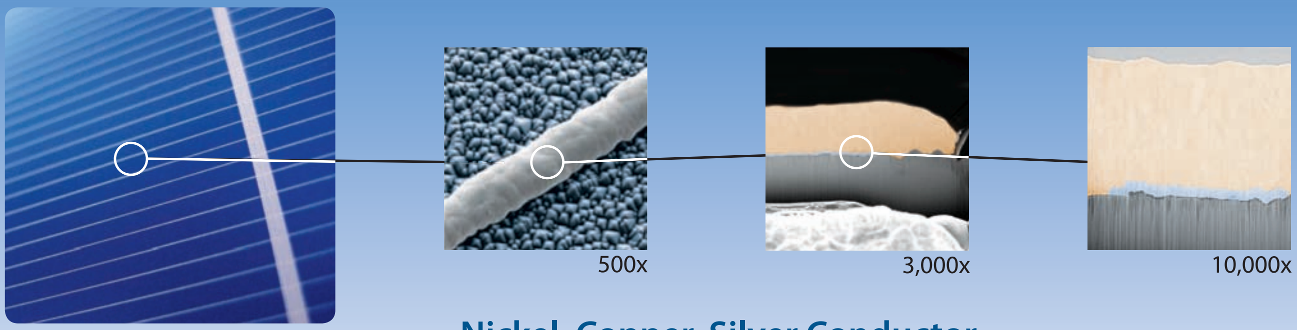

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represents a typical diffusion for large-volume production during late 2013, when the cells were procured.

The front ARC was then structured using a picosecond (ps) laser installed in a high-throughput industrial tool (Innolas), and the plating of nickel and copper and a very thin silver capping was realized in an industrially applicable inline plating tool system (RENA) using commercially available plating solutions (MacDermid). The cells were subjected to a short thermal anneal step using an industrially suitable inline furnace (BTU).

The resulting contact fingers have a semi-roundish appearance and are ~40µm wide (Fig. 2); this result was obtained without intensive optimization. The silver finish has a very bright appearance that reflects incoming light onto a large portion of the wafer surface. Through optimization of the laser process, the effective shading of the very narrow fingers can be reduced to virtually zero in the future (see the outlook discussion later).

In order to adapt the inspection system of the automated tabber–stringer system (Somont) to the very bright appearance of the plated capping layer, it was necessary to make slight adjustments to optimize the stringing process. Standard contact soldering was employed, where almost no alterations were necessary compared with a standard process.

> “While adhesion has been an issue for plated contacts in the past, the selection of a suitable laser process solves this problem.”

Solder and peel test results show that adhesion is comparable to that with standard screen-printed contacts (Fig. 3). Peel testing was carried out at a 90-degree angle to eliminate any doubt as to the actual adhesive fracture energies [17] in comparison with those for screen-printed contacts. While adhesion has been an issue for plated contacts in the past, the selection of a suitable laser process solves this problem. On removing the ARC, the laser process creates a rough surface, which is likely to improve mechanical adhesion (Fig. 4). Thermal annealing improves adhesion and contact resistance so that even a very demanding emitter with reduced surface dopant concentration can be contacted [18]. Further optimizations of the laser

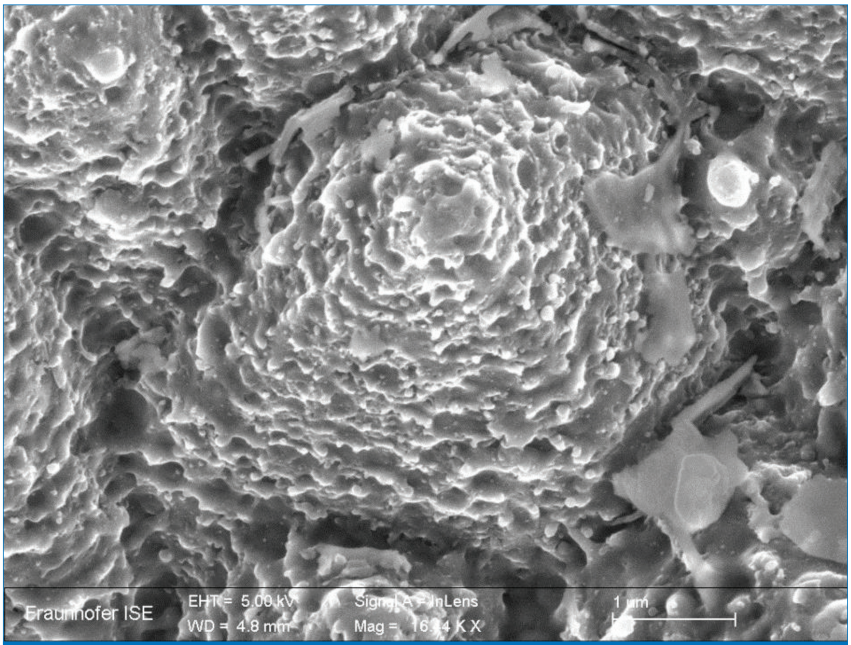

Figure 4. SEM image of the solar cell surface area with the ARC removed by ps laser ablation. The random pyramid texture shows considerable surface roughness. The space charge region remains undamaged because of the very small optical laser penetration depth (~10nm).

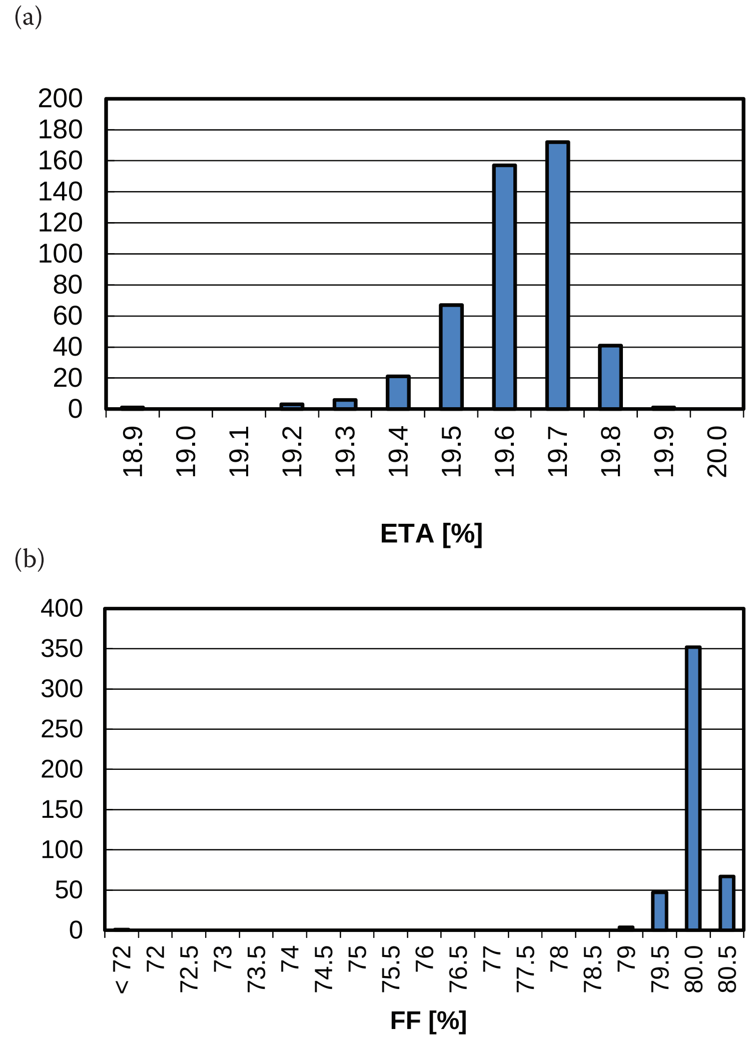

Figure 5. Cell efficiency (a) and fill factor (b) distributions achieved for several hundred Al-BSF cells featuring ps laser ablation, a nickel, copper and silver plating, and a subsequent anneal.

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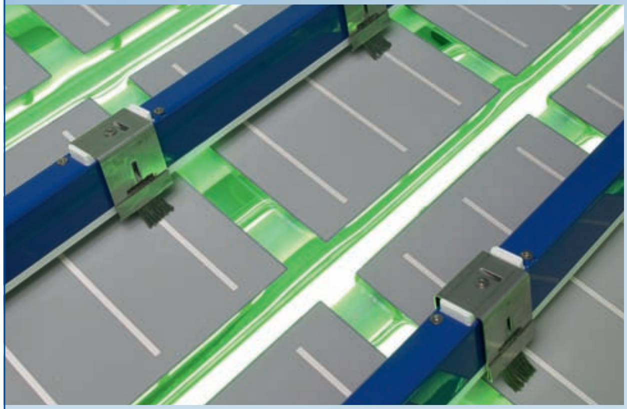

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processing might even allow the thermal step to be eliminated altogether, thereby offering a greater savings potential.

I–V measurements of the finished cells yielded a median efficiency of 19.6±0.1%, with a very neat efficiency distribution, as shown in Fig. 5(a). With respect to the metallization quality, the fill factor (*FF*) is a key parameter. Here, an even better distribution was obtained, resulting in a high average value of 80.3% and a standard deviation of 0.2% (Fig. 5(b)). The narrow distribution in electrical performance is especially noteworthy. Whereas printed cells have matured in production over many years, plated cells have yet to reach their full optimization potential in high-volume production.

From these cells, four 60-cell modules were constructed (Fig. 6) using standard module materials. After an initial characterization, the modules were subjected to climate chamber testing: thermal cycling (TC) tests (–40°C to +80°C, 200 cycles) and damp heat (DH) tests (85°C, 85% relative humidity, 1000h) were chosen in accordance with the IEC 61215 reliability testing procedure. These tests affect the metallization and are suitable for demonstrating the difficulties that plated metallization could engender at the module level.

> “Reliability testing showed no critical degradation of the modules after 1000h DH and 200-cycle TC tests.”

Reliability testing showed no critical degradation of the modules after 1000h DH and 200-cycle TC (TC 200) tests. Fig. 7 summarizes the development of the electrical parameters of two 60-cell modules for each test procedure, relative to the initial values. All modules remained well above the 95% efficiency criterion. The TC 200 test led to a slight (though not unusual) decrease in *FF*, which can most probably be fixed by optimization of the soldering process. It should be noted that, even though a few cells featured cracks (see discussion below), copper does not seem to affect module performance and reliability.

As a result of manual handling in between the automated processing steps, cracks were observed in a few cells through an electroluminescence (EL) characterization of the modules (Fig. 8). Cracking was especially evident with thermal cycling, and most likely due to crack propagation as a consequence of repeated thermal compression and expansion.

If the cracks on cells with printed and plated metallizations are compared, it becomes apparent that, despite cell cracking, separated parts of the plated cells still contribute to power generation. It has been previously reported [19,20] that a plated metallization is less sensitive to cell cracks, as the ductile plated material can compensate for slight height differences and thus all parts of the cell and module remain electrically interconnected.

Conclusion and outlook

In the experiment discussed in this paper, industrial-type solar cells were produced with a plated front-side metallization using industrial equipment and on a relatively large scale (~700 solar cells). Despite the non-optimized cell architecture, excellent cell efficiency and module stability were achieved, while front silver consumption was drastically reduced, from 120mg to 8mg per cell, resulting in as much as a $0.08/

Figure 6. Photograph of a 60-cell module incorporating nickel/copper-plated solar cells.

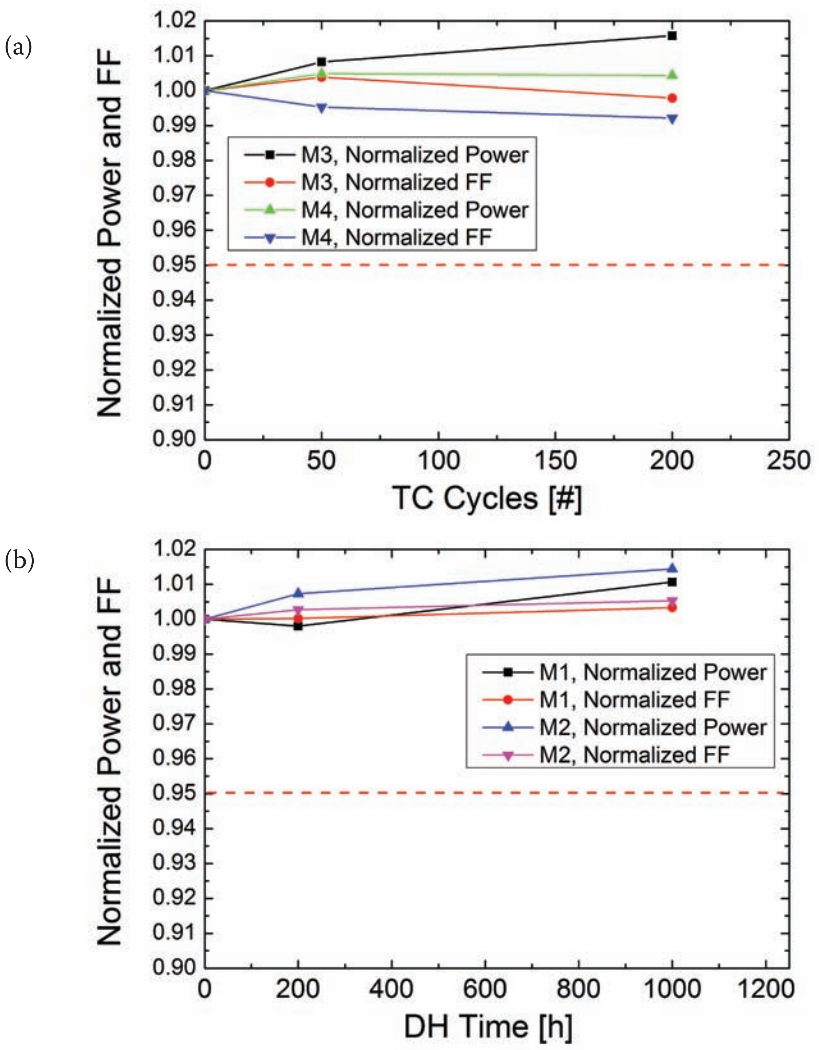
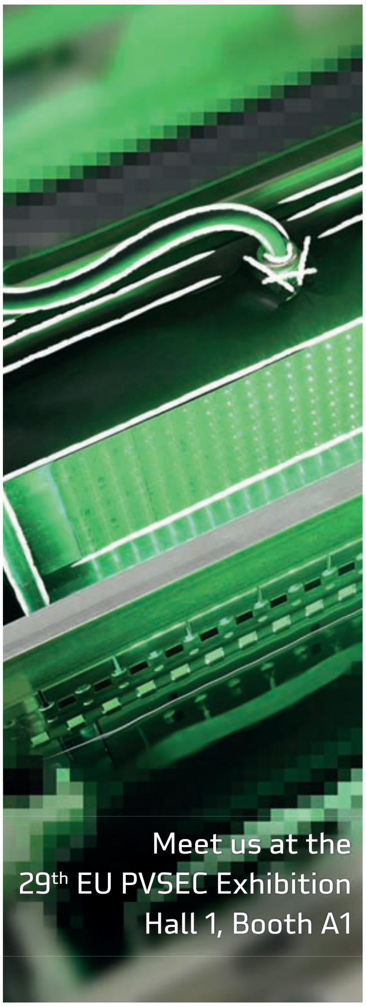


Figure 7. Results of reliability testing: (a) TC (–40°C to +80°C, 200 cycles); (b) damp heat (85°C, 85% relative humidity, 1000h). Relative power and fill factor degradation remain well above the 95% criterion (red dashed line) for all modules tested.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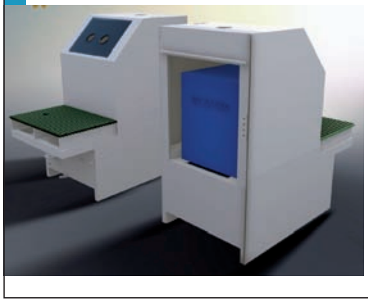

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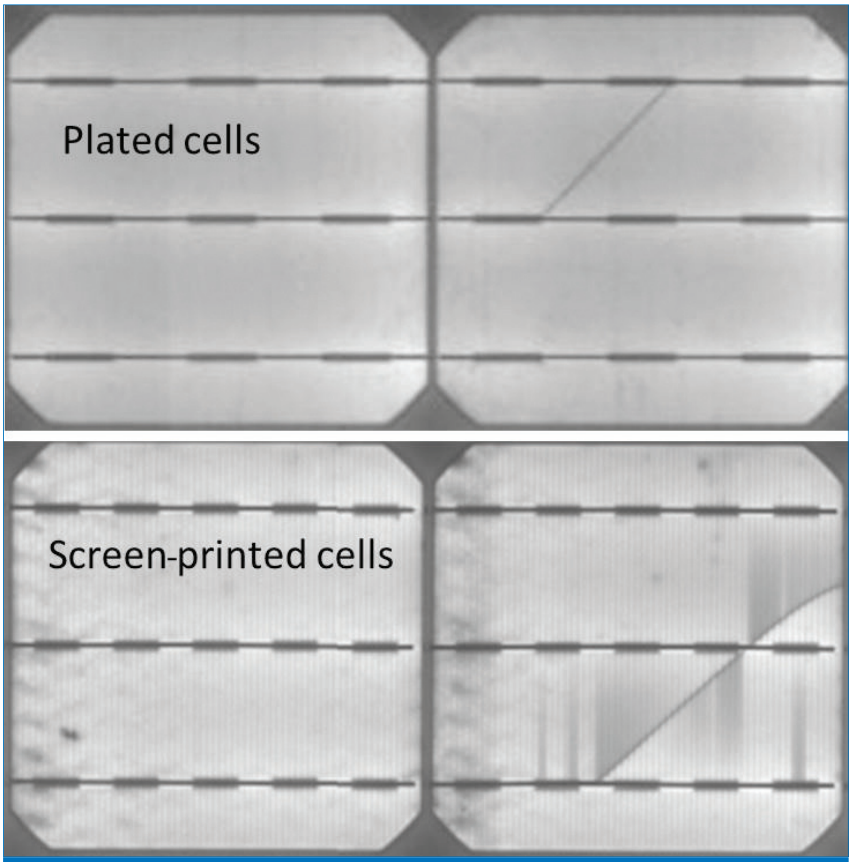

Figure 8. EL images of two cells with cracks from 60-cell modules after 200 thermal cycles. Top: plated cell metallization (this study). Bottom: typical image for screen-printed cell metallization (earlier study). The plated cells show no degradation effects (e.g. caused by copper migration or by finger interruptions). The crack in the screen-printed metallization results in breakage of the brittle finger metal and induces power loss.

cell reduction in cost. Excellent contact adhesion was obtained by employing ps laser ablation, which yielded ~20µm-wide contact finger openings with no optimization of the process.

> “Excellent cell efficiency and module stability were achieved, while front silver consumption was drastically reduced.”

In a subsequent cell run, finger widths down to 20µm were achieved, reducing finger shading to virtually zero. The construction of more modules is planned in order to improve the performance of modules with plated metallization even further by applying the knowledge gained from the present experiment. Additionally, experimental work for plated contacts on PERC-type solar cells is ongoing, and work on advanced PassDop and TopCon approaches is progressing. The benefit of a plated metallization on such high-efficiency solar cells will be even greater, having already been demonstrated in the latest PERC cell run, which yielded 21.1% efficiency.

Because of the savings in material consumption, the process is cost efficient, especially if it is kept lean. Plated conductors can ideally be complemented by physical vapour deposition (PVD) or foil metallization (using laser-fired contacts – LFC) in high-efficiency concepts. This will make large firing furnaces unnecessary and opens the path to low-temperature backend processing, which is required for advanced passivation layers. While optimization of these more advanced constructions continues, the simple process described herein is ready for production as presented, with only one process alteration – the replacement of the screen-printed conductor by plated Ni, Cu and Ag. For the first time, reliability data in large-module format demonstrates state-of-the-art adhesion and electrical performance with the lowest cost for the bill of materials.

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About the Authors

Jonas Bartsch studied chemical engineering at the University of Karlsruhe and received his diploma in 2007. He then 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 remained at ISE as head of the plating process technology team.

Andreas Brand studied physics and laser technology at RWTH Aachen, Germany, and at the University of Western Australia in Perth. He gained many years' experience with ultrashort pulse lasers and their applications while studying for his master's at the Fraunhofer Institute for Laser Technology in Aachen. In 2011 he joined the production technology and quality assurance department at Fraunhofer ISE, where he is currently working towards his Ph.D.

Dirk Eberlein received a diploma (FH) in mechanical engineering, specializing in renewable energy, from the Cologne University of Applied Science. The work for his diploma thesis was carried out at Fraunhofer ISE and concerned the development of a supersonic soldering technology for solar cells. Since 2009 Dirk has been working as a project engineer at Fraunhofer ISE in the photovoltaic modules group.

Andrew Mondon studied materials science in Freiburg, Germany, and graduated in 2010. He began working on electrochemical solar cell metallization at Fraunhofer ISE in 2009, and has been studying for his Ph.D. since June 2012, with a focus on nickel silicide formation.

Carola Völker works in the TestLab PV Modules facility at Fraunhofer ISE. She received her diploma in 2010 in mechanical engineering, with a focus on energy systems, from the University of Applied Sciences Aachen. Carola is in charge of project coordination for testing services, R&D projects and the implementation of new test facilities.

Marco Tranitz obtained his diploma degree in environmental technology at the University of Applied Sciences Jena and joined Fraunhofer ISE in 2002, where his research focuses on interconnection and solar module technology. In 2012 he completed a master's in electrical and information engineering at the University of Hagen, with a thesis topic of the series connection of solar cells by direct contact with the finger metallization.

Martin Graf received his diploma degree in physics in 2011 from the University of Augsburg in Germany. Since autumn 2011 he has been working towards a Ph.D. degree with Fraunhofer ISE in Freiburg, Germany, where his research focuses on laser-fired contacts for the foil-based rear-side metallization of silicon solar cells.

Jan Nekarda studied physics at the Ludwig Maximilian University of Munich and the Albert Ludwig University of Freiburg. He received a Ph.D. from the University of Konstanz in 2012 for his work on laser-fired contacts for crystalline silicon solar cells. Since 2011 he has been leading the laser process technology group at Fraunhofer ISE.

Ulrich Eitner studied technical mathematics at the University of Karlsruhe (TH), Germany. From 2006 to 2011 he worked in the field of thermomechanics of PV modules at the Institute for Solar Energy Research Hamelin (ISFH) and obtained his Ph.D. from the University of Halle-Wittenberg in 2011. Dr. Eitner has been managing the photovoltaic modules group at Fraunhofer ISE since 2011.

Daniel Philipp is head of the module testing group at Fraunhofer ISE, where he is responsible for reliability and certification testing of PV modules. He has been working in the field of service life analysis of modules and materials since receiving his diploma in environmental engineering and renewable energies from the FHTW Berlin in 2005.

Markus Glatthaar studied physics at the Eberhard Karls University, Tübingen, Germany, and received his Ph.D. in 2007 from the Albert Ludwig University of Freiburg in the field of organic solar cells. From 2008 to 2010 he carried out postdoctoral work at Fraunhofer ISE on the characterization of silicon solar cells, mainly on photoluminescence imaging methods. In 2011 he was a senior solar cell technologist at RENA GmbH. Since 2012 he has been head of the novel processes department within the solar cell development and characterization division at ISE.

Enquiries

Dr. Jonas Bartsch
Fraunhofer ISE
Heidenhofstr. 2
79110 Freiburg
Germany

Tel: +49 761 4588 5737

Email: jonas.bartsch@ise.fraunhofer.de
Website: www.ise.fraunhofer.de