Status of FolMet technology: How to produce PERC cells more cheaply than Al-BSF cells

Jan Frederik Nekarda[1], Martin Graf[1], Oliver John[1], Sebastian Nold[1], Henning Nagel[1], Dirk Eberlein[1], Achim Kraft[1], Rico Böhme[2], André Streek[3] & Ralf Preu[1]

[1]Fraunhofer Institute for Solar Energy Systems ISE, Freiburg; [2]Innolas-Solutions GmbH, Krailling; [3]Laserinstitut Mittweida, Mittweida, Germany

ABSTRACT

R&D activities related to solar cell production technology generally aim for higher cell efficiencies and lower production costs in order to decrease the levelized cost of electricity (LCOE). Today the passivated emitter and rear cell (PERC) is poised to become the preferred state-of-the-art cell architecture. 'FolMet' technology – a new metallization and contacting upgrade – therefore has particular relevance to PERC gains. By means of single laser pulses, conventional aluminium foil is mechanically fixed onto the cell's rear side, and local electrical contacts are formed at the same time. Coated foil enables the use of standard interconnection and module technology, which makes the FolMet procedure easy to implement in existing production lines, as well as offering outstanding potential for reducing the total cost of ownership (TCO). This paper summarizes the current state of research regarding laser process development, PERC process chain simplification and cell efficiencies, module integration and reliability, and the cost of ownership calculation.

Introduction

In the first attempts to create a rear electrode from aluminium foil at Fraunhofer ISE in 2005, 15μm-thick aluminium foil from a discount store was simply applied to a wafer and fired in a fast firing belt furnace. In the next development stage an adjusted laser-fired contact process was used to successfully increase the adhesion between the foil and the wafer [1]: the foil is locally melted by means of several single laser pulses from a pulsed nanosecond infrared laser. If enough laser power is applied, the foil is partially penetrated by the initial pulses, resulting in melting throughout the foil. The molten aluminium penetrates the dielectric layer of the passivated emitter and rear cell (PERC) and forms an electrical contact to the silicon, as well as a mechanical bond to the solar cell. The adhesion was sufficiently increased, and FolMet technology was invented as a metallization concept for PERC solar cells. The procedure is shown in Fig. 1; the approach was first published in 2007 [2], and a patent was granted in 2008 [3].

"The handling of the aluminium foil is extremely important for process quality."

From the outset, the handling of the aluminium foil is extremely important for process quality, since wrinkles lead to an incomplete non-contacted area. In 2011 a foil-handling automation

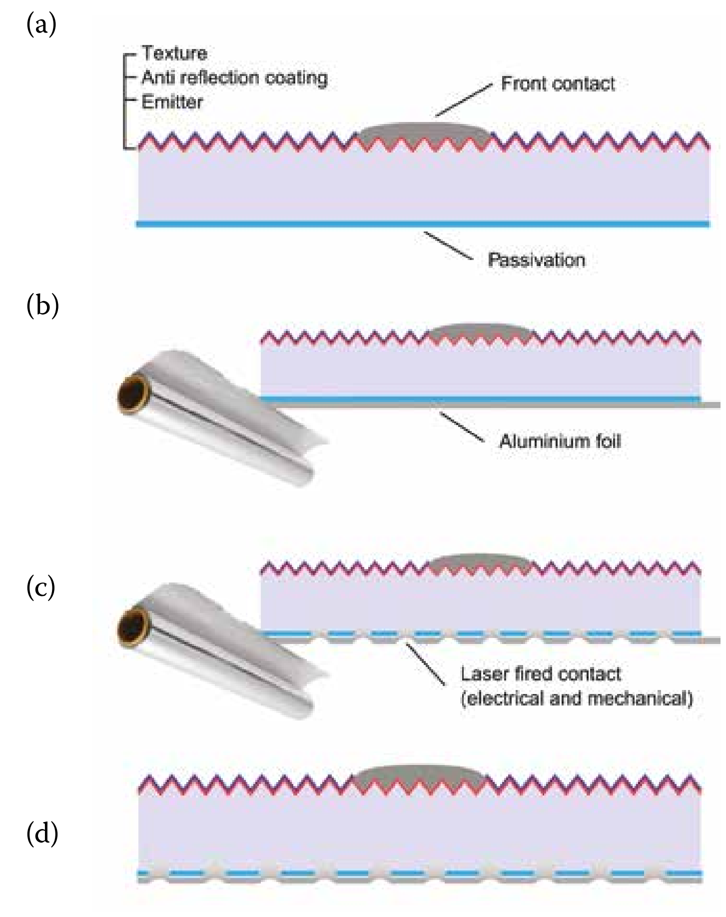

Figure 1. Process flow of the FolMet approach: (a) a precursor cell with passivated rear side and finished front-side contacts; (b) aluminium foil is rolled onto the passivated rear side; (c) laser-fired contacts are applied; (d) the foil is cut out along the wafer, yielding the ready-made solar cell.

Cell Processing

[4] was constructed, and efficiencies above 21% were achieved with high-efficiency cells for the first time [5]. At the beginning of 2013 Fraunhofer began the publicly funded project 'FolMet' with its partner Innolas-Solutions. Since then, an alpha pilot-line tool has been set up at Fraunhofer, and different issues were investigated, such as laser process optimization, adaptation of the process chain, cost of ownership and module capability. The results of this project demonstrate the huge potential of FolMet technology to further increase the efficiency of PERC solar cells, as well as to significantly decrease production costs. On the other hand, the results also highlight the remaining challenges for a successful commercialization of the technology.

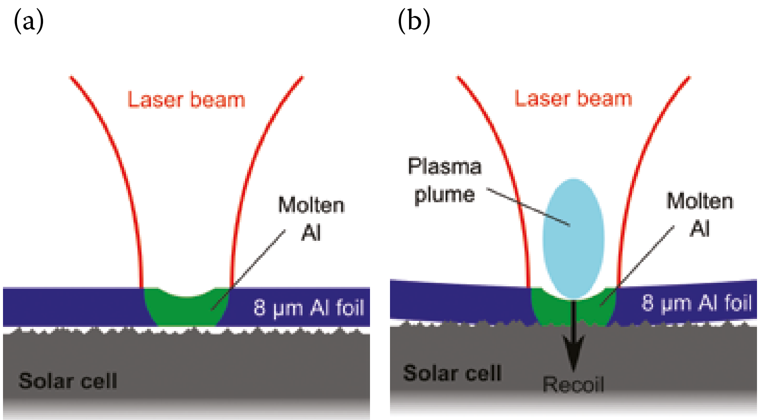

Figure 2. Schematic cross sections of the rear side of a solar cell during the laser contacting process: (a) penetration depth of the melting aluminium front (green) through the solid aluminium foil (blue), with a total thickness of 8µm; (b) plasma plume (cyan) of the evaporated material, leading to a recoil downwards to close the air gap between the foil and the solar cell (grey) under the irradiated area.

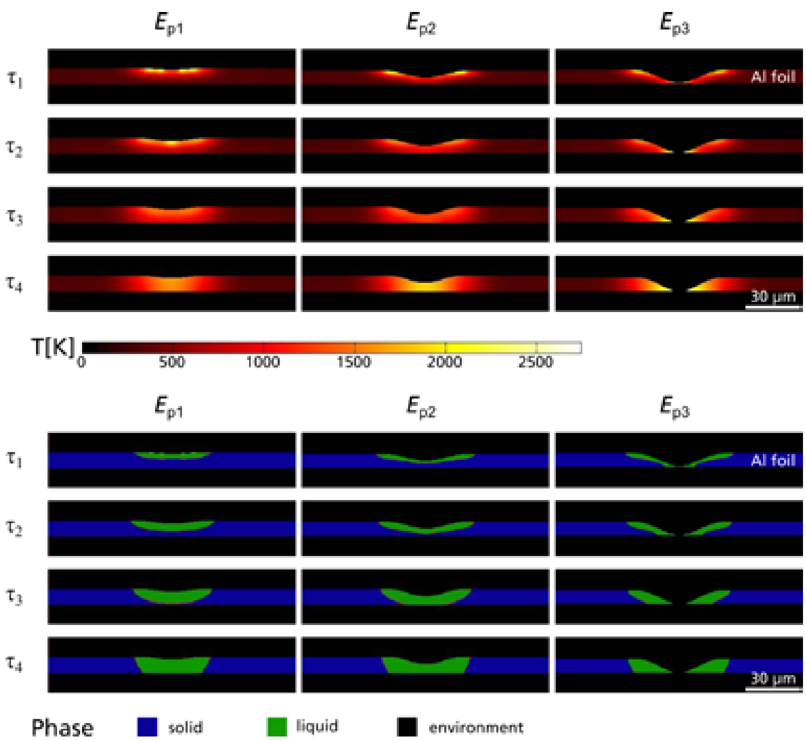

Figure 3. Influence of three different pulse energies ($E_{p1} < E_{p2} < E_{p3}$) at various pulse durations ($\tau_1 < \tau_2 < \tau_3 < \tau_4$) on the maximum temperature distribution (top) within the aluminium foil, and the corresponding phase (bottom) [7].

Current status of the laser process development

Process simulation and acceleration

The aim of the laser process is to alloy local contacts which not only provide sufficient mechanical adhesion of the foil, but also possess excellent electrical properties. To achieve any mechanical adhesion whatsoever, the foil has to be locally pressed towards the silicon surface during the alloying process. This can be realized by using a laser intensity that is sufficiently high to cause local surface heating of the foil above the evaporation temperature.

In the current process model a so-called *plasma plume* is formed, and its recoil pressure pushes the foil towards the silicon wafer (Fig. 2). To simultaneously create a permanent adhesion, the region of laser-melted aluminium must stretch over the entire thickness of the foil in order to guarantee a coating of the foil–wafer interface. Furthermore, the molten aluminium front, which is penetrating right through the foil, has to reach the interface before the plasma plume dissipates. The motion of this melting front, as well as the appearance of the plasma plume, can be tuned by choosing an appropriate laser pulse energy and pulse duration.

To better understand the influence of the above-mentioned laser parameters, a comprehensive simulation based on the finite-differences method was carried out in cooperation with Laserinstitut Mittweida [6,7]. The pulse energy E_p and the pulse duration τ were varied. The results in Fig. 3 illustrate the phase changes during the process. For a constant pulse energy E_{p1} (leftmost column), increasing the pulse duration leads to a greater melting depth. On the other hand, increased pulse energies result in deeper penetration of the foil by the melting and evaporation fronts; a laser power that is too high, however, can lead to a complete evaporation of the material, leaving behind hardly any molten material for wetting and contact formation. These results were recently experimentally validated [7,8]. It appears that a large process window exists, which allows further room for improvement, for instance in terms of optimization of the quality of the local back-surface field (BSF). However, all processes which produce sufficient adhesion of the foil have so far also yielded low-ohmic electrical contacts.

A scanning system was also evaluated: this allows the appropriate process to be quickly applied to a complete 156cm × 156cm solar cell. With that system in place, process times of less than one second, acceptable for industrial production, were demonstrated.

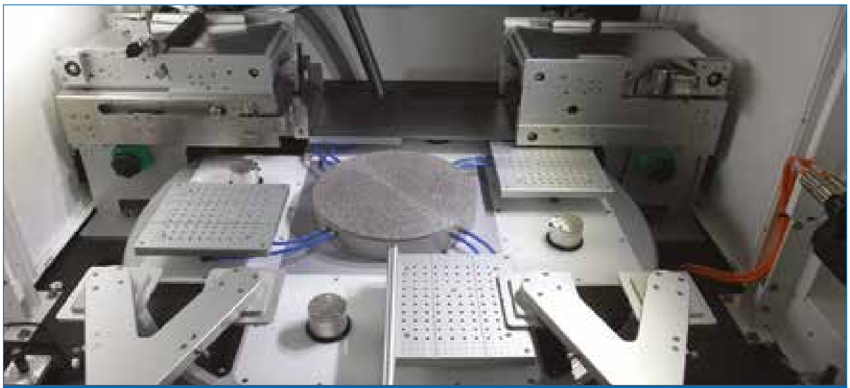

Figure 4. The FolMet alpha tool with an integrated automated foil-handling system, installed at Fraunhofer ISE.

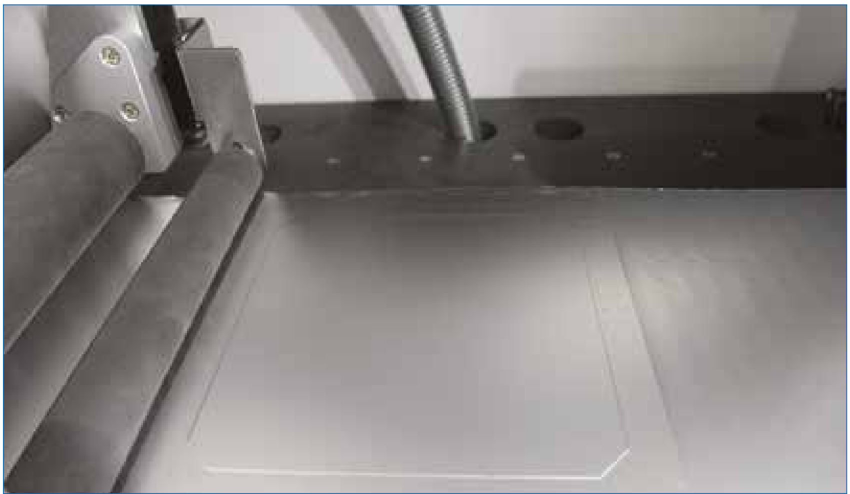

Figure 5. Homogeneous attachment of the foil onto an industrially sized solar cell precursor before the laser process begins.

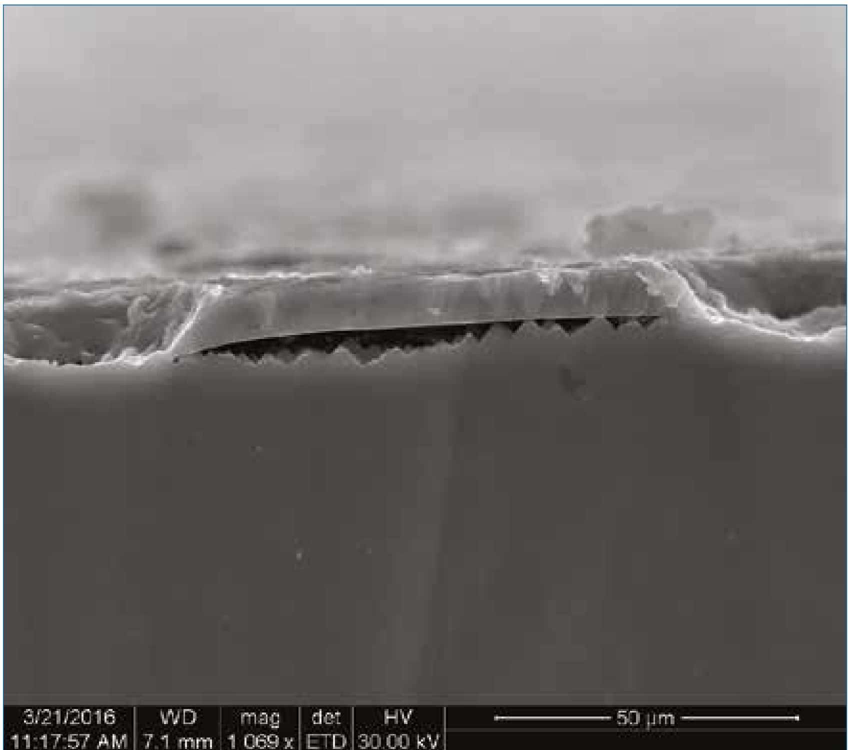

Figure 6. SEM image showing a polished cross section of a textured silicon wafer, covered by an 8µm-thick aluminium foil. On the right and left sides of the image, the foil is fixed onto the wafer by a laser-fired contact. Between these contacts a gap between the foil and the silicon wafer is clearly visible.

Tool development

Within the FolMet project, Fraunhofer's partner Innolas-Solutions developed an alpha pilot-line tool, which is based on its well-known turntable (TT) platform (Fig. 4). A foil-handling system was developed and integrated, automatically feeding foil from a 20kg roll, which is sufficient for performing the rear metallization of more than 28,000 cells. The foil is applied onto the wafer, and local contacts are formed using the laser process previously described.

Next, the foil is cut out along the edges of the cell, and the leftovers of the foil are automatically removed. The tool enables homogeneous attachment of the foil to the whole wafer before laser processing begins (Fig. 5); this, in the authors' opinion, is one of the most important requirements for FolMet technology. The throughput is still limited, however, because of the integrated laser contact formation process. In cooperation with Innolas-Solutions, a beta machine, with a target throughput of up to 2,000 wafers/hour, is currently under development.

"Homogeneous attachment of the foil to the whole wafer before laser processing begins is one of the most important requirements for FolMet technology."

Advantages of the technology

FolMet technology offers various advantages over common PERC metallization technology, which increase the efficiency potential of the cells and allow a significant reduction in costs at the same time.

Enhanced rear-side reflection

With the FolMet approach, the electrical losses are decreased. This can occur, for instance, because of the higher conductivity of the foil compared with the porous and impure post-alloy Al paste, or because of the smaller non-metallized non-contacted area along the wafer edge as a result of the limitations of screen printing in aligning to the wafer edges.

More significantly, however, the optical losses are reduced. In the first internal quantum efficiency (IQE) measurements taken in 2007 [2], the enhanced reflection of the rear side of a cell metallized with an aluminium foil became evident. Different ray-tracing simulations have indicated that an air gap between the foil and the wafer is responsible for this phenomenon, which was independently predicted in parallel by Z. Holman. In the case of FolMet, the existence of this gap was recently verified experimentally by scanning electron microscope (SEM) images on polished cross sections, as seen in Fig. 6. Not only does the air gap significantly increase the overall rear-side reflection for customary passivation layer stacks from Al_2O_3/SiN_x (as seen in Fig. 7), but it also allows the optimization of the stack in terms of surface passivation and costs, almost independently of its optical properties. A cost of ownership analysis reveals the considerable impact of reducing or completely eliminating the SiN_x capping layer.

To analyse the impact of capping layer thickness on the photogenerated current density J_G, simulations using the PV Lighthouse wafer ray tracer [9] were carried out (Fig. 8). For this, a random-pyramid-textured front and rear was utilized, as well as a 75nm-thick front-side SiN_x layer with a refractive index of 2.03 and a 6nm-thick Al_2O_3 layer. The rear-side SiN_x layer had a refractive index of 1.99, and the air gap was assumed to be 3µm thick. The consistently high J_G values for low thicknesses, and even without any capping nitride at all, demonstrate that theoretically a very thin Al_2O_3 layer, which could also be deposited by atomic layer deposition technology (ALD), yields the highest short-circuit current densities.

The influence of such PERC rear-side passivation layer stacks on the open-current voltage V_{oc} potential were investigated by measuring implied V_{oc} (iV_{oc}) using the quasi-steady-state photoconductance (QSSPC) method [10]. For this, samples were prepared with state-of-the-art cell front-side architecture, but without electrodes, and a rear side featuring a 20nm Al_2O_3 passivation by plasma-enhanced chemical vapour deposition (PECVD) and different capping layer thicknesses.

Since the SiN_x and Al_2O_3 layers require a high-temperature treatment in order to achieve maximum passivation quality, all samples were measured before and after the mandatory fast firing process. The results shown in Fig. 9 clearly underline that without a firing step, thicker layers lead to higher iV_{oc} values, probably because the wafer temperature increases during the deposition for such layers. However, after the mandatory firing step, the highest iV_{oc} values can be achieved, even without any capping layer. Unlike screen printing and firing, the FolMet approach does not impair the passivation in any way. Thus, FolMet technology yields excellent optical and electrical cell performance by the use of a significantly simplified rear passivation.

The next step was to investigate whether or not these excellent properties can be preserved at the module level. Solar cells with 0nm-, 10nm- and 100nm-thick SiN_x capping layers were therefore fabricated and their optical properties measured. FolMet was used for the metallization, while a 2µm-thick electrode created via physical vapour deposition (PVD) served as a reference. The cells subsequently underwent a standard module lamination process, and the IQE was measured. The results show that the IQE levels of the FolMet-metallized cells for both 10nm and 100nm SiN_x capping layer thicknesses are the same after lamination, and that these cells clearly outperform the reference cells (Fig. 10). This demonstrates that the thin air gap is not affected by the lamination process.

In addition, the V_{oc} potential of modules featuring FolMet-metallized cells with reduced SiN_x capping was measured after several state-of-the-art endurance-testing procedures, such as damp heat, humidity–freeze and temperature cycling. The results (see 'Module testing' section) clearly show no degradation at the module level. This again demonstrates that, in combination with FolMet, the SiN_x layer can be reduced by at least 80%, to a thickness of 20nm. Total elimination of the layer still seems feasible, but it has not yet been possible to fully demonstrate this at the module level.

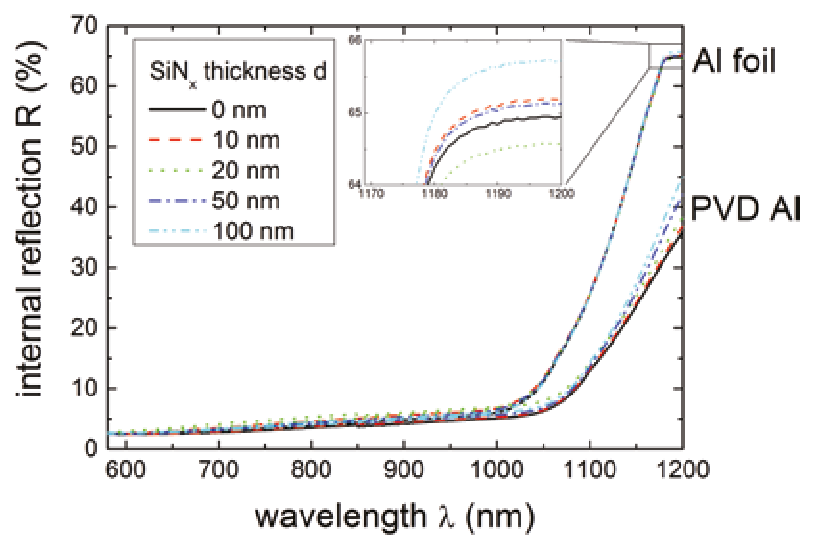

Figure 7. Measurement of the internal reflection in the 600–1,200nm range, after foil attachment and laser-fired contacts, as a function of SiN_x capping layer thickness [11].

		V_{oc} [mV]	J_{sc} [mA/cm^2]	FF [%]	η[%]
LCO (39)	Mean	657	38.9	79.1	20.2
	Best cell	659	38.1	79.4	20.4
FolMet (24)	Mean	659	39.3	78.4	20.3
	Best cell	660	39.5	78.8	20.5

Table 1. Comparison of the measured *I–V* parameters for 39 standard LCO PERC cells and 24 cells metallized with FolMet [12].

High-efficiency potential

The high-efficiency potential of the FolMet concept has already been demonstrated several times. In 2013 the FolMet approach was directly compared with the common PERC process featuring local contact opening (LCO) by laser, in combination with Al screen printing [12]. A precursor wafer from the pilot line of partner Roth & Rau was used, and the LCO reference group was fully processed at its facility. The precursors are made of large-area 156mm × 156mm magnetically grown Czochralski silicon wafers (MCz), with a base resistivity of ρ = 1.0Ω·cm.

The front side covers an emitter that has a sheet resistance of approximately 80Ω/sq. and is passivated by a PECVD SiN_x layer. In addition, to obtain lower-reflection properties, a second layer was deposited on top of the SiN_x. This side also features standard screen-

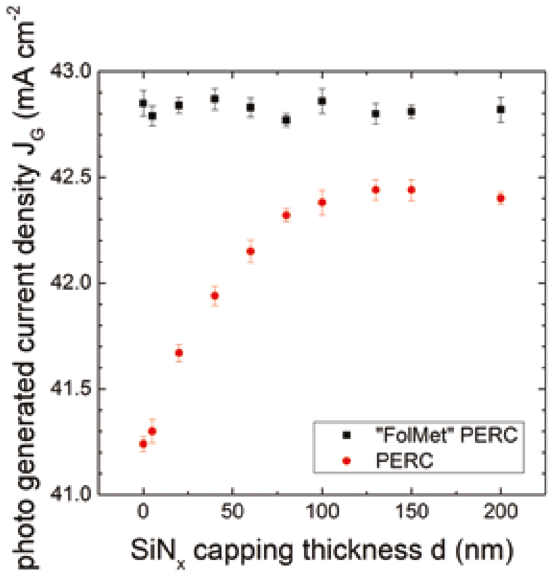

Figure 8. Simulation (PV Lighthouse) of the photogenerated current density of a FolMet rear side (black) and customary screen-printed PERC rear metallization (red), as a function of different SiNx capping layer thicknesses (assuming random-pyramid-textured front and rear sides) [9].

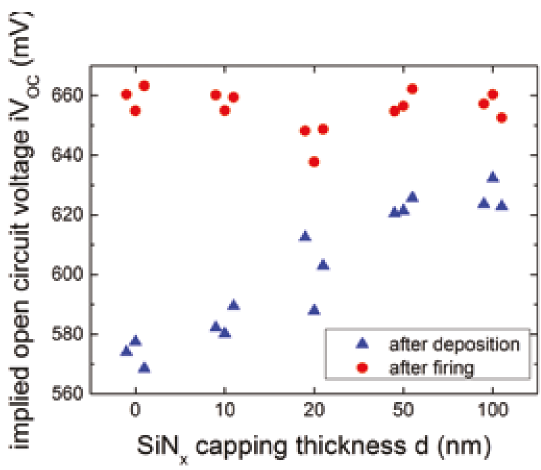

Figure 9. Implied V_{oc}, measured directly after deposition of the capping layer, and after fast firing [11].

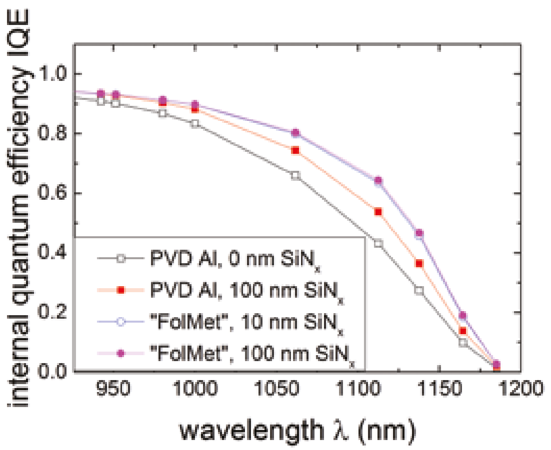

Figure 10. IQE measurements of cells with FolMet and PVD metallization, featuring standard Al_2O_3 passivation with different SiN_x thicknesses after lamination.

printed and fired contacts. The rear side is wet-chemically polished and passivated by a 120nm-thick Al_2O_3/SiN_x stack, deposited by PECVD. Of these precursors, 39 were finished with the common LCO process flow, and 24 were metallized using FolMet.

The FolMet group achieved the highest average efficiency (20.3% mean value), as well as the highest value for the best cell (20.5%), as shown in Table 1. The smaller fill factor (FF) of this group is most likely due to the significantly reduced contact fraction of the rear side compared with the LCO group. The remarkable increase in short-circuit current density J_{sc} of the FolMet-metallized cells is caused by an improved internal reflection and thus a higher IQE in the long-wavelength range. The highest V_{oc} values are also achieved with foil metallization. Despite the inferior quality of the local BSF compared with the standard PERC cells, the FolMet approach benefits from much smaller contact fractions and from the fact that there is no harmful influence on the passivation quality between the contacts.

> "FolMet technology was successfully combined with a laser-structured and plated front side, and efficiencies of 21.0% were achieved on a large-area solar cell."

In 2014 Fraunhofer ISE published efficiencies of 21.0% on large-area 156mm × 156mm solar cells with a 10nm SiN_x rear-side capping, which again were processed from precursors made by partner Roth & Rau [11]. Then, in 2015, for the first time FolMet technology was successfully combined with a laser-structured and plated front side, and efficiencies of 21.0% were achieved on a large-area solar cell (Table 2). Featuring a typical 100nm-thick SiN_x layer on the rear, this cell was almost silver free and was completely processed at Fraunhofer [13].

Simplified cell manufacturing

The full potential of FolMet technology can be exploited when making the foil solderable for standard module interconnection (see next section); Fig. 11 shows the exceptional simplification of the process chain for this case. Two extensive screen-printing processes, as well as the commonly used laser contacting opening processes, are completely replaced by the single FolMet process. In addition, FolMet enables the use of a substantially reduced rear-passivation process, and further facilitates the optimization of the front-electrode firing process, which today is always a trade-off between best front- and rear-contact qualities.

Simplified interconnection technology for conventional module integration

An important constraint of today's metallization technology is that it must facilitate solderability for standard interconnection technology. It therefore entails ordinary silver pads, which are printed on the wafer to achieve similar conditions to those of the front-side electrode, since the front and rear electrodes are simultaneously soldered to symmetric interconnection ribbons. These pads need an extra printing and drying step, consume costly silver, lead to a non-contacted p region on the rear side of the solar cell, and often require an elaborate adaptation of the soldering conditions in order to achieve a proper solder connection of sufficient strength.

The FolMet approach offers the possibility to work with single-side pre-coated foil; hence new materials other than silver can be utilized which are cheaper and offer a better compatibility with tin-coated copper ribbons, resulting in improved long-lasting solder connections. Finally, these materials do not affect the solar cell, since they are deposited only on one side of the foil, which faces away from the silicon. Local contacts can therefore be applied homogeneously, and no regions have to be left out. Such foil coatings are both easy and cheap to manufacture using a roll-to-roll process, before the foil is attached onto the solar cell, thus reducing the mechanical stress to a minimum.

Three different roll-to-roll deposition technologies are currently under investigation. Among these is a wet-chemical process that was developed at Fraunhofer ISE [14]. The Al foil is dipped in a wet-chemical solution for 90–180 seconds at room temperature. After the foil has been rinsed and dried, standard Sn/Ag/Pb-coated Cu ribbons can be soldered onto it using conventional contact or infrared soldering at standard temperatures, between 240 and 275°C. The average peel force of the ribbons was about 1.1N/mm (90° peel test), which complies with the DIN EN 50461 standard (>1N/mm). Several mini-modules were fabricated with this technology (Fig. 12) and have successfully undergone various standard testing procedures (see 'Module testing' section).

Total cost of ownership (TCO) analysis

The most distinct advantage of FolMet technology is its cost-saving potential. A detailed TCO analysis was therefore conducted of the production costs of different process sequences which are required to perform the metallization and contacting of the rear side; Al-BSF, standard PERC and FolMet PERC were compared. The firing process is not considered, since it is a necessary step in all of the three approaches because of the front-side contact formation.

> "The most distinct advantage of FolMet technology is its cost-saving potential."

The economic analysis features a bottom-up calculation of industrial cell production sequences. The underlying cost model conforms to the Semiconductor Equipment and Materials International (SEMI) standards E35 (calculation of cost of ownership) [15] and E10 (equipment reliability, availability, maintainability and utilization) [16]. The model takes into account all costs related to equipment, building and facility, labour, spare parts, utilities, process consumables, waste disposal and yield loss.

For the most part, industrial equipment and material suppliers were consulted for data. In the case of the FolMet process, all costs refer to an industrial production case and are based on estimations which take into account experience gained with

	V_{oc} [mV]	J_{sc} [mA/cm^2]	FF [%]	η[%]
Mean (6)	658	40.2	78.8	20.9
Best cell	658	40.3	79.1	21.0

Table 2. Latest *I–V* results of industrial-sized PERC solar cells featuring FolMet metallization technology.

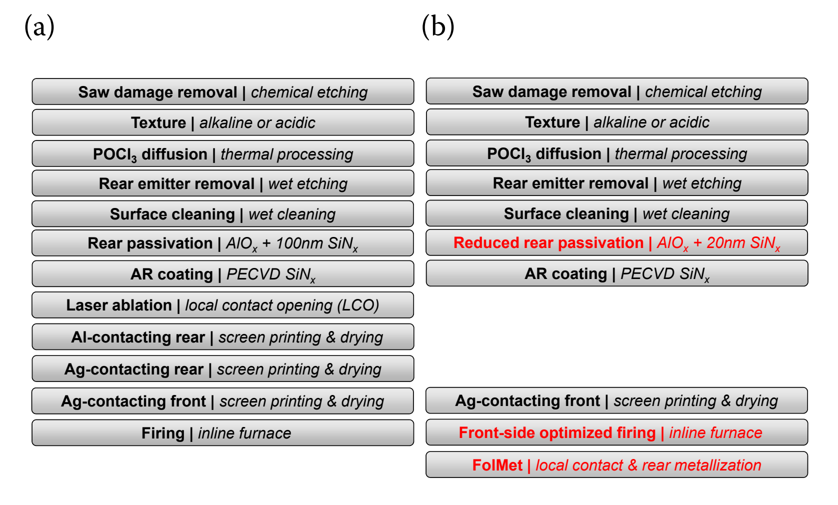

Figure 11. Schematic representation of the process flow of: (a) a state-of-the-art PERC production process; (b) a FolMet PERC production process.

Figure 12. One of the first four-cell mini-modules made from FolMet PERC solar cells (using pre-coated aluminium foil) in combination with standard PV soldering technology.

Fraunhofer's alpha tool. The cost of consumables includes the aluminium foil, which was single-side coated using the wet-chemical process described earlier. Again, the cost associated with an industrial roll-to-roll coating process was estimated on the basis of lab experience regarding consumables and waste disposal. For the coating machine, data were sourced from an established tool supplier in this field.

In Fig. 13 the production costs per cell are shown in €¢/cell, broken down for the different process steps and cost categories. It can be seen that the standard PERC rear electrode requires the most processes, which consequently results in the most expensive production costs at 17.25€¢/cell. The Al-BSF cell requires only two screen-printing processes (apart from firing), which amounts to production costs of 10.03€¢/cell. Even cheaper than conventional Al-BSF processing is FolMet technology: it also requires just two processes, namely passivation and FolMet, with resulting production costs of 8.84€¢/cell. It should be noted, however, that the indicated labour costs take into account typical German salaries; therefore the cost advantage presented will be lower for Asian production sites, since labour is required in advance for the screen-printing process steps. Nevertheless, the cost estimations for FolMet technology were carried out in a conservative fashion.

An upgrade capex of €300k is assumed for the integration of a foil-handling system within industrial laser equipment. With this conservative assumption, no capex-driven cost reduction is expected with the use of FolMet. However, the key cost advantage of the FolMet concept is the reduction in the material cost of the back contact: the aluminium and silver paste is replaced by a solderable aluminium foil. It therefore appears that the costs for one PERC cell with an efficiency potential of more than 21% can be cut down, to even below those for one of today's Al-BSF solar cells.

Module testing

A durability and lifespan analysis of modules is always an important aspect with new technologies. In the case of FolMet, the relevance is even greater for several reasons. First, materials other than Ag are used to provide solderability. Second, the foil is fixed onto the wafer only at the local contacts, and thus on about 1% of the cell area; an investigation into whether thermal broadening results in internal friction, which can lead to detachment or rupturing of the foil, is therefore necessary. Third, the influence of a reduced SiN_x capping layer on the rear side needs to be analysed.

To these ends, several one- and four-cell mini-modules were fabricated during the last few years, featuring either a glass or a polymer backsheet on the rear side; cells with 10, 20 or 100nm SiN_x were used. Standard interconnection technology was employed for soldering Sn/Ag/Pb-coated Cu ribbons on top of the coated Al foil. EVA was used as an encapsulation material, and standard lamination process were applied.

To avoid any influence of light-induced degradation (LID), the modules were exposed to a light intensity of 0.2 suns for 36 hours at a temperature T < 40°C in order to fully activate the boron–oxygen complex. Next, the most-relevant accelerated ageing tests were performed: from the authors' perspective, these are humidity–freeze for 10 cycles (HF10), temperature cycling for 200 cycles (TC200) and damp heat for 1000 hours (DH1000),

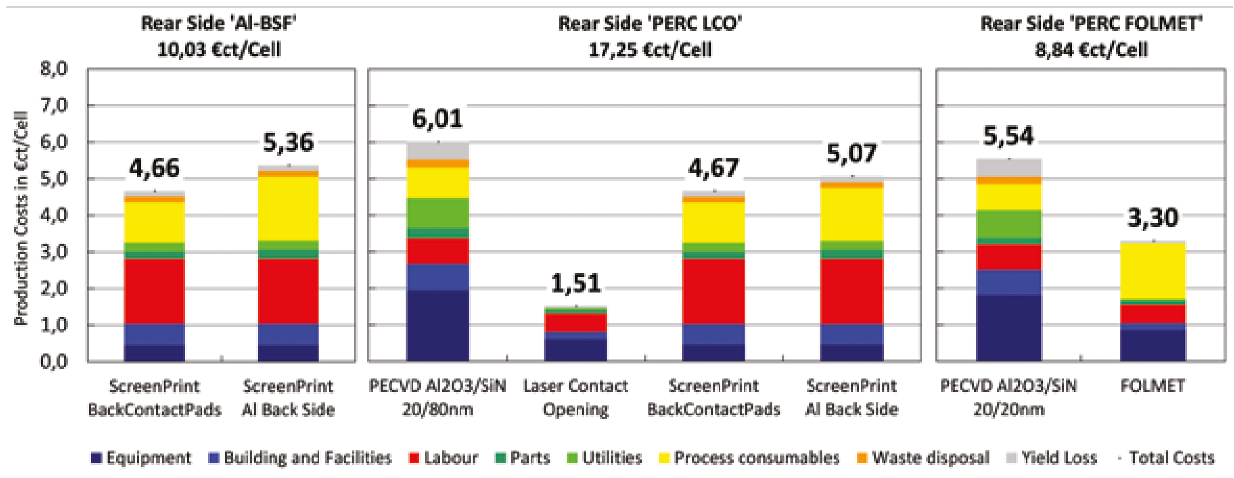

Figure 13. Production-cost analysis of the back-end process chains required for manufacturing the rear electrode. Three different approaches are compared – Al-BSF, standard LCO PERC and FolMet.

all in accordance with IEC 61215. *I–V* measurements were carried out both before and after each test.

In order to pass a test, the maximum power drop must not exceed $5\%_{rel}$; however, among the frequently tested variations, not all modules passed these tests. Nevertheless, it has recently been shown that all three tests can be passed with the use of a similar configuration of cell and module design featuring a reduced SiN_x layer thickness of 10–20nm and an aluminium foil with a solderable layer. Table 3 presents the results of these tests: there is a strong indication that solar cells with a FolMet metallized rear side can be successfully integrated in long-lasting modules which satisfy the necessary standards.

		V_{oc} [mV]	I_{sc} [A]	FF [%]	P_{mpp} [W]
HF10	Initial	2610	8.77	72.51	16.60
	After	2630	8.78	72.15	16.63
	Rel. dev. [%]	0.6	0.1	–0.5	0.2
TC200	Initial	632.8	9.11	75.08	4.33
	After	628.6	9.10	74.00	4.23
	Rel. dev. [%]	–0.7	–0.1	–1.4	–2.2
DH1000	Initial	630.1	9.08	74.91	4.28
	After	616.8	8.90	75.07	4.12
	Rel. dev. [%]	–2.1	–2.0	0.2	–3.8

Table 3. Measured *I–V* parameters of mini-modules before and after humidity–freeze (HF10), damp-heat (DH1000) and temperature-cycling (TC200) tests.

Summary and outlook

The current state of development of the so-called *FolMet* technology has been presented. A first alpha tool has been set up at Fraunhofer ISE, enabling proper handling and attachment of the Al foil. The laser process is thoroughly understood, and the parameter space for the most-relevant laser parameters is well known. A significantly process acceleration has already been demonstrated, allowing process times below one second to be realized.

FolMet technology offers improvements in the optical properties of the cells and modules, and significant simplifications in the process flow at the same time. The technology further allows easy integration into standard module lines by the use of solderable foil. This feature can be easily achieved by cheap roll-to-roll deposition processes, which offer several additional advantages. With a coating developed in-house, mini-modules created using a standard interconnection soldering technique could already be successfully manufactured today. Moreover, such modules have passed the most-relevant module endurance tests, namely humidity–freeze, damp heat and temperature cycling.

"FolMet technology offers improvements in the optical properties of the cells and modules, and significant simplifications in the process flow at the same time."

On the basis of Fraunhofer's FolMet experiences, as well as with data from an industrial partner, a cost of ownership calculation was performed. The results not only demonstrate the significant cost-saving potential compared with standard LCO PERC technology, but clearly indicate that the FolMet approach can push down costs per cell even below those of today's Al-BSF cells, while still allowing cell efficiencies of above 21%.

To carry on the development of this promising technology, and to prepare its readiness for industrial production, a publicly funded project has been initiated in collaboration with several industrial partners. The focus of this will be: 1) the development of a beta machine with a higher throughput; 2) further optimization of the laser process; 3) the benchmarking of different foil-coating processes for solderable layers; and 4) a detailed long-term stability analysis.

Acknowledgements

The authors would like to thank all co-workers at Fraunhofer ISE, as well as all other partners for their individual support and contributions. This work was supported by the German Federal Ministry for Economic Affairs and Energy, within the FolMet research project under Contract No. 0325574.

References

[1] Schneiderlöchner, E. et al. 2001, "Laser-fired contacts (LFC)", *Proc. 17th EU PVSEC*, Munich, Germany, pp. 1303–1306.

[2] Nekarda, J. et al. 2007, "Aluminum foil as back side metallization for LFC cells", *Proc. 22nd EU PVSEC*, Milan, Italy, pp. 1499–1501.

[3] Grohe, A. 2007, "Method for metallization of solar cells and its application" [in German], DE 102006044936 B4.

[4] Nekarda, J.-F. 2012, "Laser-fired contacts (LFC) - Characterization, optimization and modelling of a process for locally rear-side contacting dielectrically passivated solar cells" [in German], Ph.D. dissertation, Faculty of Physics, University of Konstanz, Freiburg im Breisgau.

[5] Nekarda, J.-F. et al. 2010, "Comparison of the three different metallization concepts for LFC cells", *Proc. 25th EU PVSEC*, Valencia, Spain, pp. 2245–2249.

[6] Streek, A. 2016, "Laser micro sintering", Ph.D. dissertation, Technical University of Dresden [forthcoming].

[7] Graf, M. et al. 2015, "Comprehensive simulation and acceleration of the foil-metallization laser process", *Energy Procedia*, Vol. 77, pp. 694–700.

[8] Graf, M. et al. 2015, "Foil metallization process for PERC solar cells towards industrial feasibility", *Proc. 31st EU PVSEC*, Hamburg, Germany, pp. 386–389.

[9] McIntosh, K.R. et al, "PV Lighthouse – Wafer ray tracer" [http://pvlighthouse.com.au/calculators/wafer ray tracer/wafer ray tracer.html].

[10] Cuevas, A. et al. 1998, "Applications of the quasi-steady-state photoconductance technique", *Proc. 2nd WCPEC*, Vienna, Austria.

[11] Graf, M. et al. 2014, "Progress in laser-based foil metallization for industrial PERC solar cells", *Proc. 29th EU PVSEC*, Amsterdam, The Netherlands, pp. 532–535.

[12] Nekarda, J. et al. 2013, "Laser-based foil-metallization for industrial PERC solar cells", *Proc. 28th EU PVSEC*, Paris, France, pp. 797–799.

[13] Alemán, M. et al. 2009, "Advances in electroless nickel plating for the metallization of silicon solar cells using different structuring techniques for the ARC", *Proc. 24th EU PVSEC*, Hamburg, Germany, pp. 1414–1418.

[14] Nagel, H. 2016, "Enabling solderability of PVD Al rear contacts of high-efficiency crystalline silicon solar cells by wet chemical treatment" [forthcoming].

[15] SEMI 2012, "Guide to calculate cost of ownership (COO) metrics for semiconductor manufacturing equipment", E35-0312.

[16] SEMI 2014, "Specification for definition and measurement of equipment reliability, availability, and maintainability (RAM) and utilization", E10-0814.

About the Authors

Jan Frederik Nekarda studied physics at Ludwig Maximilian University in Munich and at Albert Ludwig University in Freiburg. He joined Fraunhofer ISE in 2005 and received his Ph.D. from the University of Konstanz in 2012. Since 2010 he has been head of the laser process technology group at Fraunhofer ISE, and is a co-inventor of FolMet technology.

Martin Graf received a Diploma degree in physics from the University of Augsburg in 2011. He has been working towards a Ph.D. with Fraunhofer ISE in Freiburg since 2011, with a research focus of laser-fired contacts (LFC) for foil-based rear-side metallization of silicon solar cells.

Oliver John was awarded his M.Sc. in physics by the Albert Ludwig University in Freiburg in 2014. He subsequently began research within the laser process technologies group at Fraunhofer ISE, where he is currently working on his Ph.D. concerning improvements to FolMet technology.

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 been with Fraunhofer ISE since 2008, working in the fields of cost calculation, technology assessment and economic evaluation of new concepts in the production of silicon solar cells. He is currently completing his doctoral thesis at ISE on the techno-economic assessment of new silicon PV production technologies along the PV value chain.

Henning Nagel received his Ph.D. in physics from the Institute for Solar Energy Research (ISFH) in Hamlin. He worked for 11 years in the R&D department at SCHOTT Solar, where he developed processes and equipment for solar cell and module production, and was also team leader of the cell simulation and characterization group. In 2013 he joined the solar cell development and characterization division at Fraunhofer ISE as a project manager.

Dirk Eberlein studied renewable energies at the Cologne University of Applied Sciences, Germany. Since 2009 he has been working in the module technology group at Fraunhofer ISE as a project engineer.

Achim Kraft studied electrical engineering at the University of Applied Science in Hanover, and renewable energies at the University of Applied Science in Berlin. He received his Ph.D. in 2015 in the field of plated copper front-side metallizations for silicon solar cells from Albert Ludwig University of Freiburg, Germany. Since then his research has focused on solar cell interconnection technologies and processes as head of the interconnection technologies team in the module research group at Fraunhofer ISE.

Rico Böhme received his Ph.D. in 2007 from Martin Luther University in Halle-Wittenberg, Germany. From 2008 to 2011 he worked for Roth & Rau as a process engineer, and in 2012 joined Innolas-Solutions, where he manages the R&D activities.

André Streek completed professional training in informatics and electronics. He studied physical engineering at the University of Applied Sciences Mittweida in Germany, after which he joined Laserinstitut Mittweida as an R&D engineer. Now a scientist within the company, he mainly focuses on fast laser material interaction, fast scanning systems and additive manufacturing.

Ralf Preu is director of the PV production technology and quality assurance division at Fraunhofer ISE. He received a Diploma degree in physics in 1996 from the University of Freiburg, Germany, and a Ph.D. in electrical engineering in 2000, followed by a Diploma degree in economics in 2003 from the University of Hagen.

Enquiries

Jan Nekarda
Fraunhofer Institute for Solar Energy Systems ISE
Heidenhofstraße 2
79110 Freiburg
Germany

Tel: +49 (0)761 4588 5563
Email: jan.nekarda@ise.fraunhofer.de