FoilMet®-Interconnect: Busbarless, electrically conductive adhesive-free, and solder-free aluminum interconnection for modules with shingled solar cells

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Abstract
The investigation of novel cell-to-cell interconnection methods has gained importance with the increase of wafer sizes. Shingling (i.e., overlapping) of solar cells is not only a solution for the interconnection of smaller solar cells but also a chance to increase the output power density by (i) increasing the active cell area within the module, (ii) decreasing shading losses, and (iii) reducing electrical interconnection losses. Replacing the commonly used expensive materials such as the silver in the cell's electrodes and the electrically conductive adhesive increases the attractiveness of a shingled interconnection. This article introduces the FoilMet®-Interconnect, an approach using laser-welded aluminum foil, for shingling and presents two solutions for configuration. With the production of aluminum foil-based shingle strings and modules, saving 36.7% of silver, a proof of concept was successful. In subsequent measurements, an efficiency of $\eta_{\text{FoilMet}} = (21.0 \pm 0.2)\%$ was achieved with foil-based strings of three shingled cell. Temperature cycle tests after encapsulation indicate the applicability and durability of the approach.

KEYWORDS
bonding, FoilMet, interconnection, laser, shingle, solar cell, welding

1 INTRODUCTION

The fabrication of silicon wafers and cells trends towards larger formats that reach to around 210-mm edge length.1 Large cells, however, result in higher currents, which cause the series resistance contribution of the modules metallization to increase in effect. One way to counteract this loss is the reduction of the resistance by enlarging the effective cross section of the metallization. This, however, leads to higher consumption of precious resources as silver (Ag) or copper and magnifies shadowing effects. Another way to reduce the cell interconnection losses is the reduction of string currents by interconnecting separated, that is, smaller, solar cells such as half cells2–10 and shingle cells.3,11–19 Conventional shingling also increases the consumption of Ag20 due to the necessity of busbar and Ag containing electrically conductive adhesives (ECAs), however, reduces shadowing effects. Since increased recombination occurs at postfiring separated edges, the cell pieces cannot be chosen arbitrarily small and a compromise between the reduction of series resistance and increase of edge recombination must be found. Nevertheless, the market share for modules of separated silicon solar cells has gained relevance.1 Down sizing the cell pieces by separation after the cell contact formation could therefore be one way to achieve higher module efficiencies.
Described in the patent of Dickson in 1956, shingling of solar cells is performed by the overlap of adjacent solar cells. This allows a large part of metallization to be located in the space between the cells and thus outside the active cell area. Cells interconnected this way can be packed particularly tight, hence allow significant fewer gaps in the module. This contributed in a variety world records for module efficiencies over nearly three decades.

The metallization of a solar cell typically consists of a screen-printed Ag electrode on the front side and an aluminum (Al) and/or rear Ag electrode (Figure 1A). Since shingling is based on metallization with a front and a rear electrode, most cell concepts are compatible with the production of shingle strings including bifacial cells. The typical approach to interconnect shingle cells is based on using ECAs connecting the rear side busbar of one cell to the front side busbar of an adjacent cell (Figure 1B). ECAs are polymer-based adhesives that are filled with electrically conductive particles as Ag (approximately 50–80 wt%). The function of the polymer is to give adhesion to the surfaces and mechanical strength. The particles form a three-dimensionally electrically conductive network. Besides ECA bonding, there are other ways to create shingled or gapless modules such as tiling.

As the commercialization of ECA-based shingle modules just took place in the 2010s (e.g., Sunpower and Solaria), the experience with reliability of this technology is still limited compared to conventional interconnection approaches. A focus of recent research is the understanding of thermomechanical stress in the ECA joint. The thermomechanical stress is caused by temperature changes and different thermal expansion coefficients of the module materials that mainly lead to shearing and bending at the shingle joint. The right choice of ECA and processing conditions considering aspects such as adhesion strength, mechanical flexibility of the material, conductivity, and bond line geometry is believed to result in good thermomechanical long-term stability.

Because of the low price of Al compared to copper or Ag and because laser welding of Al with IR lasers is well-understood, the usage of Al foils in solar manufacturing is of high interest and was investigated repeatedly.

2 | MATERIAL AND METHODS

2.1 | FoilMet®-Interconnect

FoilMet®, which is in the process of patenting, addresses the above problems by means of laser-welded Al foil. First, it presents a cost-effective and flexible solution for the interconnection of separated cells. Second, it holds a high potential of conserving resources, and third, it has a potentially increased string efficiency due to lowered series resistance in the Al-foil joint.

The front side metallization of a passivated emitter and rear cell (PERC) shingle cell consists of repetitive fingers and a busbar (Figure 1A). The fingers connect the emitter through the front side passivation with the busbar forming the front screen-printed Ag electrode. The rear electrode is formed by several Ag pads or a single busbar and Al fingers covering the laser contact openings (LCOs) in the rear passivation. The busbar of the front is connected with solder or more typically ECA to the busbar of the rear metallization of the neighboring cell (Figure 1B-D).

In our novel concept, we omit the ECA and the screen-printed busbar on both sides (Figure 1C) and replace it with an 8-μm-thick Al foil (EN AW-8079). The Al foil is directly joined to the silicon nitride (SiNₓ) passivation using the so-called laser metal bond (LMB) process. The Ag fingers and the Al fingers are microwelded to the foil using 300- to 700-μm-long line-shaped joints performed with a single 1-kW infrared continuous-wave laser leaving no necessity for busbar-like structures. The simplicity of FoilMet, which connects the fingers of adjacent cells without more intermediate layers than a single Al foil, is of great advantage compared to an ECA interconnection, with joints from the Al finger to the Ag busbar, to the ECA, to the Ag

![Figure 1](https://example.com/figure1.png)
busbar, and to the Ag finger, and therefore consisting of a multitude of layers.

2.2 Laser metal bond

LMB\(^{12}\) is a noninvasive joining technique that enables the formation of bonds between the passivation of the cell and the Al foil without penetrating the passivation (Figure 2A). This does not create an electrical contact but a very high adhesion between the Al foil and the wafer. Since the passivation remains intact, almost no additional charge carrier recombination occurs.\(^{44}\) For the formation of the LMB, the Al foil needs to be in direct contact with the cell surface. This is achieved on a vacuum chuck. A screen-printed body, however, serves as a spacer and thus prevents a proper LMB formation. Therefore, a certain lateral distance between the LMB and the screen-printed metal contact (for, e.g., finger) is required, which depends on how high the metal contact protrudes above the level of the cell, as well as the thickness and ductility of the foil. An LMB placed in a sufficient large gap between surrounding screen-printed bodies achieves an adhesion of \(0.080 \pm 0.011\) N per LMB. On the other hand, an LMB close to or on a screen-printed body results in drastically reduced adhesion. Depending on the arrangement and density of the LMB, adhesions can be obtained that exceed the tear strength of the Al foil.

2.3 Al–Al weld

The joint of the Al foil to the Al fingers (Al–Al weld) was realized with the same laser device. As visualized in the cross section (Figure 2B), there is no mixture of the two substrates. Nevertheless, measurements applying 4-wire sensing prove an excellent electrical conductivity of the joint as expected form a metal–metal interface. In peel tests, the fracture did not occur in the joint but within the screen-printed contact or between the screen-printed contact and the wafer. To simplify the production of the cells in the following experiments, no special Al–Ag welds were used on the front. Instead, the entire surface of the front junction was densely covered with LMB, which also contact the front-side metallization. The Al–Ag adhesion in this configuration is poor, however, due to the support of the surrounding LMB sufficient. An ion polished cross section reveals a fracture at the welding point (Figure 2C), however, measurements applying 4-wire sensing witness low resistance of the joint.

2.5 Implementation for shingling via Al foil

Two different ways to produce shingle strings with the connections described above were examined. In the first configuration, two cells are placed on top of each other with their front sides facing each other (Figure 3A). Al foil is placed on both cells with the upper cell being positioned 2 mm off-center and brought into direct contact with the substrate using vacuum. All areas which are to be lasered face the same of \((0.016 \pm 0.003)\) N per weld. The number of welds, however, is limited by the number and distance of the fingers. Therefore, it is advisable to use LMBs to increase the adhesive force. As in previous work shown,\(^{45}\) another way to produce an Al–Al weld is using a nanosecond laser. Here, a deep mixture of the substrates is achieved. The Al foil, however, is thinned out around the welding. Therefore, it is not yet clear which technique leads to higher adhesion.

FIGURE 2 Cross sections of all three joining methods polished with an argon ion polisher. The laser metal bond (A) establishes a purely mechanical connection to the cell surface and demonstrates high adhesive strength. The Al–Al weld (B) creates a low-resistance electrical connection between the Al foil and the screen-printed Al finger. The connection between the Al foil and the sensitive screen-printed Ag fingers is made with the Al–Ag weld (C).
direction and, when slightly tilted, are in the focal plane of the scanning laser system. Therefore, all laser steps can be performed at once, leading to process times in the regime of tens to hundreds of milliseconds. After all laser steps have been performed, the upper cell is folded over and remains next to the lower cell with an overlap of 0.7 to 2.5 mm (Figure 3B). The size of the overlap can be adjusted due to the flexibility of the foil forming a U shape between the upper and the lower cell.

In the second configuration, the Al foil is placed on top of the first and underneath the second cell (Figure 3C). Between the cells, there is a gap of 1 mm through which the Al foil passes from top to bottom. After all laser steps have been performed, the first cell is slid underneath the second cell with an overlap of 0.7 to 2.5 mm (Figure 3D). Due to the flexibility of the foil which forms a Z shape between the cells, the size of the overlap can be adjusted.

Regardless of the configuration, the Al foil forms a kink between the two cells which allows the interconnection to be extremely flexible. A photo (Figure 4A) of a finished FoilMet®-Interconnect string demonstrates this flexibility of the interconnection, in this case a U shape. Depending on the dimensioning of the foil and the configuration, great mobility in almost all directions is possible without exerting forces on the LMB or welds. These flexible connections can absorb the large forces generated during deformation at different
temperatures (Figure 4B). If the kink of the Al foil is chosen bigger than stated above, a placement of the cells next to each other (not shingled) is also possible.

3 | EXPERIMENTAL DESIGN

In this work, two experiments were conducted. In the first, the performance of our novel FoilMet®-Interconnect was compared with the performance of a conventional interconnection employing ECA. In the second, aging tests were performed on modules employing the FoilMet®-Interconnect.

3.1 | Rating of the performance of FoilMet®-Interconnect in comparison to ECA

In the first experiment, p-type Cz-Si PERC precursors with an edge length of 156.75 mm and 210 mm diameter were used and after pre-characterization homogeneously distributed into two groups (Figure 5A). After metallization each host cell features five rectangular bifacial shingle solar cells with a size of 22 × 156.75 mm (the two wafer parts with the pseudo-square edges are not used). The two groups were screen-printed in the same run with identical front Ag finger and identical rear Al finger metallization layouts. One group, the FoilMet® group, bypassed the screen-printing steps for the front and rear Ag busbars. After separation 10 shingle strings were produced, each consisting of three shingle cells. Six strings were adhered in a conventional way using ECA and standard end connectors, and four were joined using FoilMet®-Interconnect ending with an open lace of Al foil. The FoilMet® strings have on average (0.89 ± 0.46) mm larger overlap per interconnection than their ECA reference due to manual handling and therefore a smaller active area. The active area consists of all visible cell area in the module including Ag fingers but excluding areas covered by Al foil as in the end connections or stretched interconnections (Figure 7B). I–V measurements were performed for all strings by contacting the end connectors, respectively Al foil laces with kelvin clamps.

3.2 | Analysis of the aging process of FoilMet®-Interconnect in the module

In a second experiment, other precharacterized bifacial p-type Cz-Si PERC host cells with an edge length of 156.75- and 210-mm diameter were separated into six solar cells with a size of 26.125 × 156.75 mm. The four rectangular-shaped shingle solar cells separated from the center of each host cell are then homogeneously distributed within five shingle strings, each consisting of six shingle cells (Figure 5B). All strings were interconnected using the foil interconnection applying the U-shaped foil configuration.

FIGURE 5 Process flow of the two experiments within this work. (A) Two groups of shingle strings were produced within the first experiment of this work. The conventionally processed strings with ECA and our novel approach with Al foil, FoilMet®-Interconnect. Process steps that differ between the two groups are highlighted. The FoilMet® group does not require a screen-printing step for rear and front Ag busbar. (B) Process flow of the second experiment. Only one group of strings was produced in a similar way as the FoilMet® group in experiment one. These strings were encapsulated and subject to a temperature cycle test.
Due to a drastically increased resistance in the interface between Al finger and Ag busbar on the cell rear, no comparable strings using ECA could be produced from the original batch. Thanks to the direct interconnection, the FoilMet strings do not possess this kind of interface and therefore are not affected by this issue. However, the experiment lacks a directly comparable reference group. To monitor the following test, two ECA strings using cells with busbars from another batch were added to the group of FoilMet® strings and subjected to the same procedure.

All strings were laminated with module materials in a plate-membrane vacuum laminator and subjected to a thermal cycling test from −40 °C to 85°C at 25% rh. I–V measurements and electroluminescence (EL) images were taken before and after lamination as well as after 50 (TC50) and 200 (TC200) temperature cycles. Prior to lamination, Al foil was welded to the outermost cells of the shingle string. Then, shingle string end connectors consisting of solder-coated copper were welded to these outermost laces of Al foil. This combination of Al foil and shingle string end connector adapts the foil interconnection to conventional and solderable PV module cross connectors, used as outgoing leads of the mini modules. It may be possible to directly weld the outermost Al foil to the cross connectors, but this was not tested in this work. The ECA-based references contain shingle string end connectors directly glued to the busbars of the outermost cells. The shingle string end connectors were then soldered to conventional photovoltaic (PV) module cross connectors which were used as outgoing leads like the Al foil based strings. The strings were encapsulated in a 20 × 20 cm and 3.2-mm-thick solar glass and with ethylene-vinylacetate (EVA) as well as a black single layer polyethylene terephthalate (PET) backsheet.

4 | RESULTS

In the following, we compare our novel FoilMet®,-Interconnect to the conventional interconnection using ECAs and conduct a TC200 test.

4.1 Rating of the performance of FoilMet®-Interconnect in comparison to ECA

In the first experiment, the performance of the foil interconnection was benchmarked against a conventional interconnection using ECA. The ECA strings achieved an average efficiency of \( \eta_{\text{ECA}} = (20.3 \pm 0.2)\% \). The FoilMet® group on the other hand achieved with \( \eta_{\text{FoilMet}} = (21.0 \pm 0.2)\% \) an outstanding efficiency, 0.7%abs higher than the ECA group (Figure 6). Although being bifacial, only the front side contribution of the strings was considered in its measurement.

The data for short-circuit current (Figure 6B), fill factor (Figure 6C), and open-circuit voltage (Figure 6D) imply the efficiency advantage is mainly due to the increased fill factor (\( \pm 2.5\%_{\text{abs}} \)). The series resistance was acquired using a light-forward and a dark-forward I–V curve evaluated by the double light-level method (IEC 60891).[47,48] It indicates that the welding of the aluminum foil with the Ag/Al finger has excellent electrical properties (Figure 6E).

The following reasons for the disparity of the fill factor are under discussion. (i) An increased resistance in the interface of the ECA and the screen-printed Ag busbars would explain the effect, reflected in the measurement. (ii) Also, the interface between the Al finger and the Ag busbar could have led to increased resistance contributions. However, the contact formation between Ag- and Al-screen-printing pastes is well-understood from classical monofacial cells, where similar paste combinations are used between rear Al metallization and Ag pads.[49] Nevertheless, the contact interface of an Al finger and the Ag bus bars with the bifacial PERC cells in this experiment is significantly smaller, which might pose new challenges for the connection. (iii) Due to the manual placement of the cells within the strings, the size of their active area does vary and could lead to a mismatch of the cells within the string. This would result in the fill factor being overestimated and a reduction in string current. However, evaluations of scans of both string groups show no significant misplacement, neither a reduction of string current is reflected by the measurement. Regardless of the cause leading to the disparity in the filling factor, in general,
good interconnections using ECA can be achieved. FoilMet®-Interconnect, however, demonstrates the ability to reliably create interconnections with low series resistance and strings with high efficiencies. The simplicity of FoilMet, which connects the fingers of adjacent cells without more intermediate layers than a single Al foil, is of great advantage and might be a way to improved reliability of interconnections.

During the screen-printing process, the wafers were weighed before and after the individual screen-printing steps. Therefore, the exact Ag consumption of the Ag paste with an Ag content of 91% could be determined. Since the FoilMet® cells did not require any screen-printing steps for busbars, 27.5% less Ag paste was required for their production (Figure 7). A further saving of silver results from the omission of the ECA with an Ag content of 50% and an average usage of 4 mg per interconnection resulting in a total conservation of 36.7% Ag.

4.2 Analysis of the module integration and temperature cycle cycle stability of FoilMet®-Interconnect

In order to test the capability of module integration of FoilMet®-Interconnect, a second experiment was conducted. A photograph of a module shows features of the flexible foil interconnection (Figure 8). During manual placement of the strings, the first shingle was positioned slightly tilted. In addition, the interconnection between shingles 4 and 5 was stretched, resulting in a thin strip of Al foil being visible. All laser joints for the interconnections were lasered at identical positions with high precision. The deviations in length and rotation, shown in the picture, are solely due to the flexibility of the foil interconnection, proving again their capability to absorb mechanical deformation. Placing the strings by machine would lead to uniform results.

In the I–V measurements, the strings before encapsulation show an average efficiency η_string = 20.4% (Figure 9A). After lamination, the average efficiency, normalized to the active area of the string, drops to η_modul = 19.8%. This loss, primarily visible in short-circuit current (Figure 9B), is mainly caused by reflection and absorption of the glass and absorption of the encapsulation foil in the module. A detailed analysis of the cell-to-module losses of the shingle technology is given in Mittag et al. Fill factor (Figure 9C) and open-circuit voltage (Figure 9D) remain unchanged and show the ability of the rather short six-cell strings to withstand the thermal and mechanical stresses of encapsulation; however, full-sized strings with 40+ cells undergo different stresses during processing. After the modules were subjected to a TC200 test with 200 temperature cycles, a further efficiency loss of all FoilMet® modules was measured. Three modules were measured in the limit of a maximum of −5%rel power loss given by IEC61215. The open-circuit voltage and fill factor of those modules remained stable within the errors, and the short-circuit current decreased slightly. The remaining two FoilMet® modules lost 2.4%abs, respectively, 3.0%abs in efficiency, and 9.5%abs, respectively 11.9%abs in fill factor during the TC200 test.

The ECA-based references introduced to monitor the TC test also stayed in the limit of a maximum of −5%rel power loss. As mentioned before the ECA strings were made from cells of another batch. Therefore, a direct comparison of the two groups is not possible.

EL images of all samples as strings before encapsulation, as modules and after the TC50, respectively, TC200 test were taken to increase understanding of possible failing interconnections (Figure 10). Samples 2, 3, and 5 show no signs of deterioration and convince with a comparatively high homogeneity along the cells. This homogeneity could be the result of the high transverse conductivity of the Al-foil fold. Sample 1 shows a slight deterioration of the...
connections in some areas of the right string half after the TC50 test. However, only a minor reduction of the I–V values is recognizable in comparison with the other strings. After the complete TC200 test, a further deterioration in this sample can be seen, which has a visible effect on the IV values. Sample 4 has defective connection areas from the beginning. A share of the fingers was not joined successfully. During encapsulation and especially after the TC50 and TC200 test, these areas deteriorated and led to the drop in efficiency described above. The mechanism underlying the deterioration is not known and needs to be investigated in the future. Nevertheless, with the three samples that do not show accelerated deterioration, FoilMet®-Interconnect has successfully demonstrated that connections lasting a full TC200 test can be formed.

5 | SUMMARY

In this article, we introduce FoilMet®-Interconnect, a flexible and potentially low-cost shingle interconnection without the need for screen-printed Ag busbars nor ECA. We use Al foil to replace the interconnection that is normally established with ECA. Three joining processes are introduced: The Al foil is welded directly (i) to the fingers of the rear Al-electrode, (ii) to the fingers of the front Ag electrode, and (iii) to the front and rear passivation. All three joining processes are evaluated in terms of adhesion and conductivity and are examined based on polished cross-sections.

In the first experiment, our novel shingle strings were produced and benchmarked to conventional strings using ECA. The FoilMet® strings achieved an efficiency of $\eta_{\text{FoilMet}} = (21.0 \pm 0.2)\%$. This is
0.7%\textsubscript{abs} higher than its ECA reference, most likely as a result of a low series resistance and leads to an improvement in the fill factor by 2.5%\textsubscript{abs}. During the production in this experiment, 36.7% Ag was conserved due to the unnesscity of busbars and ECA within FoilMet\textsuperscript{®}-Interconnect. In the second experiment, we produced modules with the novel interconnection concept. These modules were subjected to a TC200 test to obtain insights of the long-term stability of the Al interconnection. The majority of all shingle strings withstand the stresses of encapsulation and a TC200 test. In both experiments, it has been shown that FoilMet\textsuperscript{®}-interconnect might be a way to low-resistant and high-efficiency interconnection. Since the Al foil is bonded to the cell and welded to its electrodes, FoilMet\textsuperscript{®}-Interconnect is potentially applicable to nearly all metallization and cell concepts.

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DATA AVAILABILITY STATEMENT
The data that support the findings of this study are available from the corresponding author upon reasonable request.

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