

FOILMET®-INTERCONNECT SHINGLING (FIS): ALUMINUM FOIL BASED 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. 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.

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 increase the effect of the series resistance contribution of the modules metallization. One way to reduce the cell interconnection losses is the reduction of string currents by interconnecting separated, i.e. smaller, solar cells such as half cells [2–5] and shingle cells [6–9]. Since increased recombination occurs at the currently non-passivated cell edge, the cell pieces cannot be chosen arbitrarily small and a compromise between the reduction of series resistance and edge recombination must be found. Nevertheless, the market share for modules of separated silicon solar cells has gained relevance [1].

The typical approach to interconnect shingle cells is based on using electrically conductive adhesives (ECA) interconnecting the rear side busbar of one cell to the front side busbar of an adjacent cell [10, 11].

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 thermo-mechanical stress in the ECA joint. The thermo-mechanical 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 [12, 13]. 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 [14], the usage of Al-foils in solar manufacturing is of high interest [15].

2 MATERIAL AND METHODS

2.1 FoilMet®-Interconnect Shingling (FIS)

FIS, 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.

In our novel concept, we omit the ECA and the screen-printed busbar on both sides 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 [16]. The Ag-fingers and the Al-fingers are micro welded to the foil using 300-700 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-busbar, and to the Ag-finger, and therefore consisting of a multitude of layers.

2.2 Implementation for shingling via Al-foil

One way to produce shingle strings with the connections described is to place two cells on top of each other with their front sides facing each other (Figure 1A). 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. 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 1B). 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.

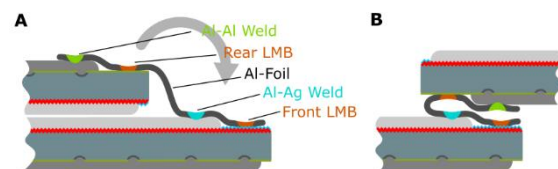


Figure 1: Sketch of different configuration creating a foil shingle string. (A) In the first configuration, the shingles are placed with their front side facing each other with a slight offset. (B) After laser processing, the top cell can be folded over. (not to scale).

Due to the configuration, the Al-foil forms a kink between the two cells which allows the interconnection to be extremely flexible. 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.

3 EXPERIMENTAL DESIGN

3.1 Rating of the Performance of FIS in Comparison to ECA

In this experiment, ten shingle strings were produced (Figure 2), each consisting of three shingle cells. Pre-characterized and within the groups homogeneously distributed bifacial p-type Cz-Si PERC host cells with an edge length of 156.75 mm and 210 mm diameter were used. Each host cell features five rectangular shingle solar cells with a size of 22 mm x 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. The FoilMet® group bypassed the screen-printing steps for the front and rear Ag busbars. Six strings were adhered in a conventional way using ECA and standard end connectors, and four were joined using FIS 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. I-V-measurements were performed for all strings by contacting the end connectors respectively Al-foil laces with kelvin clamps.

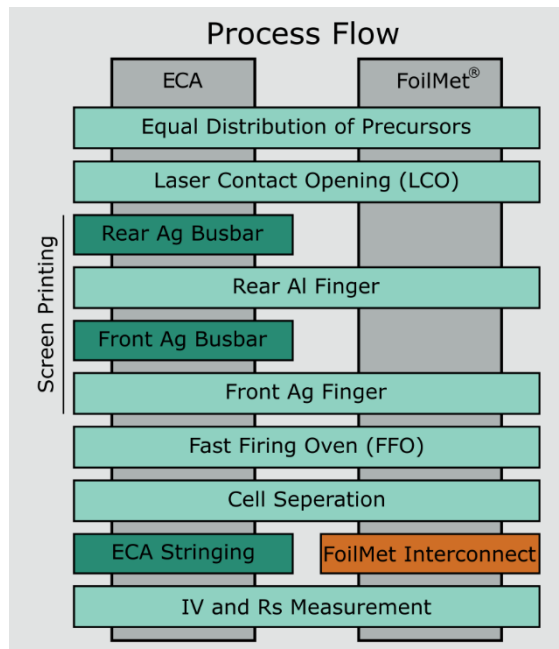


Figure 2: Process flow of the experiments in this work. Two groups of shingle strings were produced within the first experiment of this work. The conventionally processed strings with ECA and our novel approach with Al-foil, FIS. Process steps that differ between the two groups are highlighted. The FoilMet® group does not require a screen-printing step for rear and front Ag-busbar.

4 RESULTS

In the following, we compare our novel FIS to the conventional interconnection using ECAs. In this experiment, the performance of the foil interconnection was benchmarked against a conventional interconnection using ECA. The ECA strings achieved an average efficiency of $\eta_{ECA} = (20.3 \pm 0.2)\%$. The FoilMet® group on the other hand achieved with $\eta_{FoilMet} = (21.0 \pm 0.2)\%$ an outstanding efficiency, $0.7\%_{abs}$ higher than the ECA group (Figure 3).

The data for short circuit current (Figure 3B), fill factor (Figure 3C), and open circuit voltage (Figure 3D), imply the efficiency advantage is mainly due to the increased fill factor ($+2.5\%_{abs}$). It indicates that the welding of the aluminum foil with the Ag-/Al-finger has excellent electrical properties.

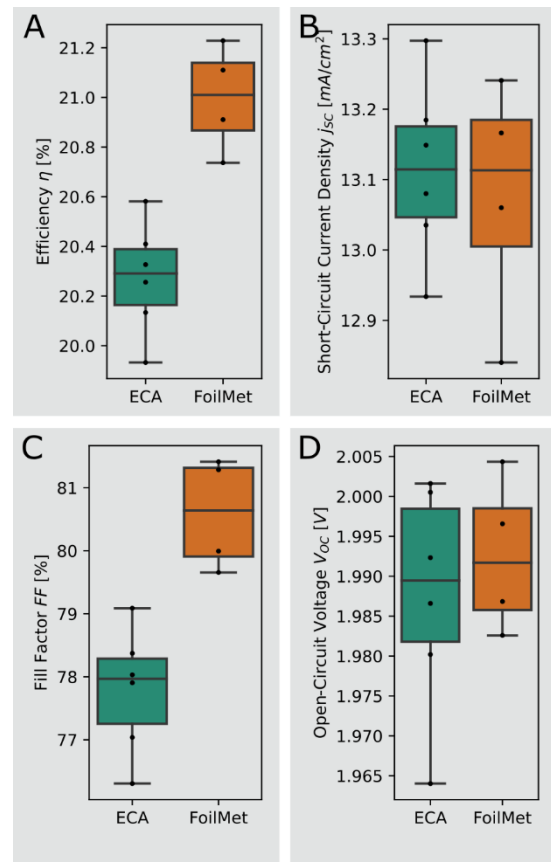


Figure 3: Comparison of strings adhered in the conventional way using ECA (ECA) and strings with the novel FIS (FoilMet). I-V-measurements of shingle strings consisting of three cells each itemized to (A) energy conversion efficiency, (B) fill factor, (C) short-circuit current density, and (D) open-circuit voltage.

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. (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. Regardless

of the cause leading to the disparity in the filling factor, in general good interconnections using ECA can be achieved. FIS, 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. 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.

5 SUMMARY

In this article, we introduce FoilMet®-Interconnect Shingling (FIS), 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 $0.7\%_{\text{abs}}$ 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 $2.5\%_{\text{abs}}$. During the production in this experiment, 36.7% Ag was conserved due to the unnecessary of busbars and ECA within FIS. In the second experiment, we produced modules with the novel interconnection concept. These modules were subjected to a TC50 test to obtain first insights of the longterm stability of the Al-interconnection. With one exception, all shingle strings withstood the stresses of encapsulation and a TC50 test. In the experiment, it has been shown that FIS 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, FIS is potentially applicable to nearly all metallization and cell concepts.

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