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Ultra-soft wires for direct soldering on finger grids of solar cells

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Abstract

We propose an interconnection concept for solar cells that enables the soldering of solder coated copper wires directly on the contact fingers of the front side metallization without the need of busbars or contact pads. By reshaping the copper wires we realize a wave-shaped stress relief structure. This reduces the yield force, the force value where plastic deformation of the wire starts, up to 90 % compared to straight wires and therefore minimizes mechanical stresses in the joint after the soldering process essentially. Our experimental analysis demonstrates the mechanical long-term stability of the interconnection (ΔP < 2 % after TC 370). The method enables a significant silver reduction by omitting solder pads or busbars on the front side and is especially suitable for the interconnection of exceptionally thin, stress sensitive solar cells or back contact solar cells with a minimized cell bow.

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Keywords: Wire interconnection; wave-shaped wires; reliability; contact fingers; thermomechanical stress; stress relief; Multi Busbar; SmartWire; temperature cycling; electroluminescence

1. Introduction

On the worldwide market, the prices for solar modules have been constantly falling for decades. Therefore, cost reduction is crucial for module manufacturers to remain competitive. One possibility to decrease costs is to reduce the content of silver in a solar module, since silver is comparatively expensive. Omitting busbars or even contact pads is one approach that targets the reduction of the amount of silver for the metallization for silicon solar cells. Unfortunately, it is very challenging to realize a reliable interconnection of a silicon solar cell only with contact fingers due to their low width of < 70 µm. At present, there are three concepts for the interconnection of solar cells without busbars:

Schmid proposes solar cells that are interconnected by infrared soldering of solder-coated copper wires on both sides using a silver-reduced Multi Busbar (MBB) layout [1]. The reliability of solar modules with MBB solar cells has been investigated, where cells feature miniaturized contact pads for solder joints [2].

The SmartWire concept of Meyer Burger enables the interconnection of pad- and busbar-free solar cells during the lamination process by using wires, coated with a low-melting solder and being pre-embedded in polymer foils [3]. This concept requires wires coated with a specific low-melting solder alloy [4].

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Schneider et al. and Geipel et al. demonstrated the interconnection of solar cells without pads or busbars by using conductive adhesives (ECA) and ribbons [5, 6] which is especially suited for non-solderable, temperature-sensitive or mechanically fragile cells. The additional cost for the ECA needs to be balanced with the specific module cost (CoO or LCOE) [7].

In this work we introduce a novel concept for a reliable interconnection of solar cells without busbars or pads by soldering copper-based wires, coated with a standard solder (Sn62Pb36Ag2), directly on the finger metallization.

2. Experiments

2.1. Adjusting the wire shape

Changing the shape of copper-based wires potentially leads to a significant change of its mechanical properties. To reshape a wire we developed a method that enables the production of wave-shaped wires with adjustable periods and amplitudes. Figure 1 shows microscopic images of wave-shaped wires with a constant period of 3.1 mm and various amplitudes.

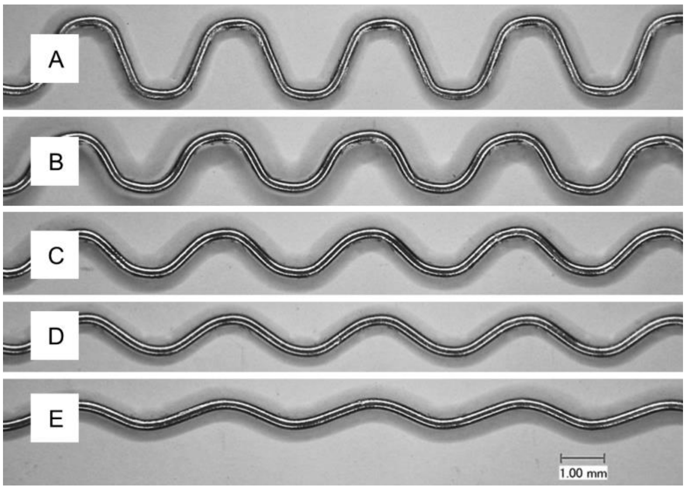

Fig. 1. Microscope images of wave-shaped wire examples with a period of 3.1 mm and various amplitudes (peak-to-peak) between 0.6 and 2.0 mm (A: 1906 µm, B: 1448 µm, C: 1166 µm, D: 1012 µm, E: 779 µm).

We measure the mechanical behavior of a wire interconnector by standard tensile tests according to ISO 6892-1 [8]. By analyzing the stress-strain-curve we obtain the Young's modulus, the yield stress and the ultimate tensile strain. During tensile testing the wave-shaped wire is straightened and the material is stretched. In contrast to the mechanical stress, we analyze the measured force since the force is independent from the geometry. In addition, for wave-shaped wires we denote the elongation level as "effective strain" because both - straightening as well as material stretching - contributes to the total strain.

2.2. Soldering on contact fingers

With a width of 40-70 µm contact fingers are particularly prone to defects due to shear stress. Walter et al. demonstrated that soldering of straight wires on contact fingers leads to instant delamination of the outermost fingers and poor adhesion forces due to the CTE mismatch of copper and silicon [1]. This is in accordance with simulation results which demonstrate that for pad-based interconnection of silicon solar cells the maximum stress is located adjacent to the outermost contact pads [9]. To analyze the potential of wave-shaped wires when it comes to the interconnection of metallization layers that show limited adhesive strength we solder six wave-shaped wires with a peak-to-peak (pp) amplitude of 1.5 mm and period of 3.1 mm on the front side of a common solar cell with a three busbar metallization layout. On the rear side we solder six wave-shaped wires with peak-to-peak amplitude of 0.8 mm and period of 1.6 mm on the contact pads. The soldering is done manually with a solder iron (240 °C) on a hot plate (~110 °C). It has to be considered that the contact finger distance (1.94 mm) and the period of the wave-shaped wires (3.1 mm) is not matched. We expect that a matching will improve the reproducibility and the reliability of the solder joints. In addition, the series resistance as well as the shading by the wires increases with the length increase due to the wave. On the front side the wires are soldered directly on the contact fingers and on the rear side two wires are soldered on each pad row. Figure 2 shows a solar cell interconnected with wave-shaped wires on both sides.

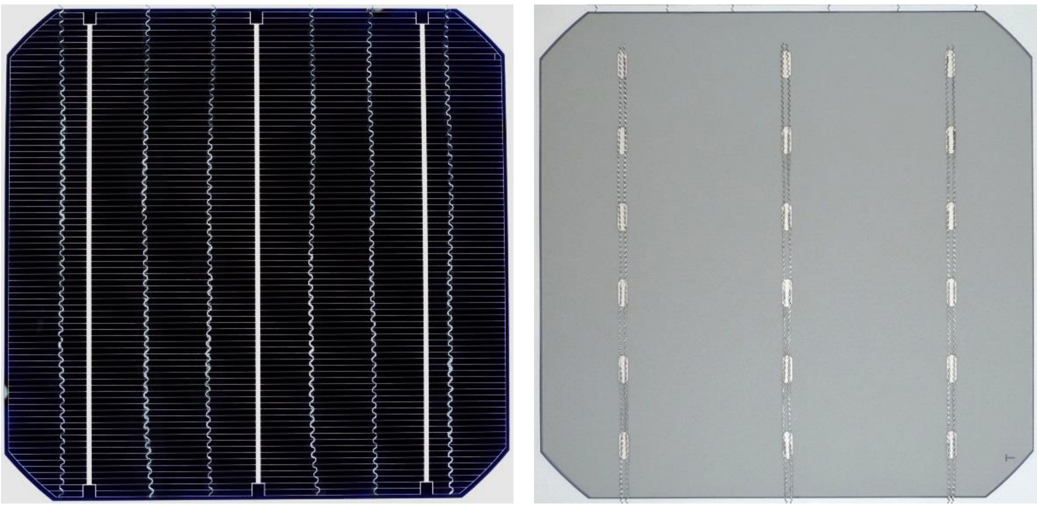

Fig. 2. Front (left) and back side (right) of a standard solar cell with a three busbar metallization layout. The solar cell is interconnected with six wave-shaped wires on both sides.

2.3. Long-term stability

To investigate the reliability of the solder joints we laminate a single solar cell with a front glass (200 x 200 x 4 mm³), EVA, and a standard backsheet and perform a temperature cycling test (-40 °C/85 °C) according to IEC 61215 [10]. In addition, an identical solar cell that is conventionally connected with three ribbons (1.5 mm x 0.2 mm, Sn62Pb36Ag2) on both sides is laminated as a reference mini-module. Prior to the temperature cycling and after different test cycles we take electroluminescence (EL) images of both one-cell-modules and measure the IV-parameters.

3. Results

3.1. Characterization of wave-shaped wires

To illustrate how the mechanical behavior of the wave-shaped wires changes, figure 3 shows the measured force-effective-strain-curves of a standard wire (black) and five wave-shaped wires (colors). To quantify the influence of the amplitude on the mechanical behavior of a wave-shaped copper wire we perform tensile tests on wires with different amplitudes. We use wires with a copper core (Cu-ETP1, diameter: 300 µm) and a solder-coating (Sn62Pb36Ag2, thickness: 10-15 µm). In the measured curves we determine the force value where we have 0.2 % plastic deformation and define it by 0.2 % yield force $F_{0.2\,\%}$.

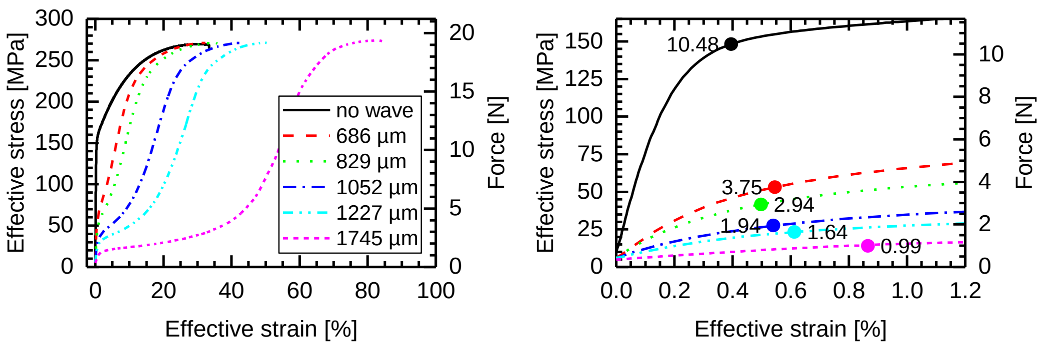

Fig. 3. The left diagram shows the entire stress-strain-curve of a wire with a copper core diameter of 300 µm (black line) and the force-effective-strain-curves of wave-shaped wires with various amplitudes (colors). On the right side the measured curves are displayed between 0 and 1.2 % strain. In addition the 0.2 % yield force $F_{0.2\,\%}$ of each sample is shown.

We measure the mechanical behaviour of six different wire groups, each including five specimens. Table 1 shows the mean value of amplitude and $F_{0.2\,\%}$ for the different specimen groups. The results show a reduction of $F_{0.2\,\%}$ with increasing amplitude of the wave-shaped wires. Even with the lowest amplitude of 686 µm $F_{0.2\,\%}$ is reduced by 64 % compared to a straight wire. By increasing the amplitude to 1745 µm we determine a maximum reduction of $F_{0.2\,\%}$ of 90 % compared to straight wires.

Table 1. Mean values of $F_{0.2\,\%}$ and the measured amplitude (peak to peak) of wave-shaped wires with a period of 3.1 mm and various amplitudes.

Measured amplitude (peak-to-peak) (µm)	no wave	686	829	1052	1227	1745
$\boldsymbol{F_{0.2\,\%}}$ **(N)**	10.35	3.69	2.98	1.95	1.64	1.03
Relative reduction (%)		64	71	81	84	90

3.2. Investigation of the solder joint reliability by temperature cycling

Figure 4 shows the EL images of the one-cell-module interconnected with wave-shaped wires after the lamination process (left) as well as after 370 temperature cycles according to the IEC test standard (right). The initial EL image of the test module shows a fully interconnected solar cell with some slightly darker areas that can be explained by contact finger defects after the soldering process due to the CTE mismatch. After 370 temperature cycles we determine an increasing number of darker areas, where the degradation caused by thermomechanical stress becomes visible.

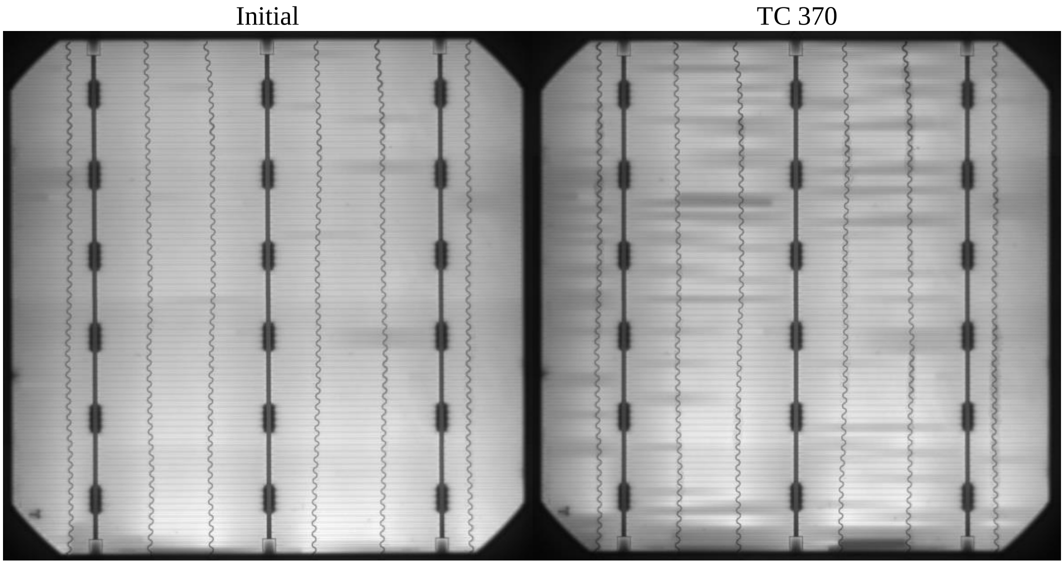

Fig. 4. EL measurements of a solar cell connected with six wave-shaped wires on both sides. The front side is shown after the lamination process (left) and after 370 temperature cycles according to the IEC standard (right).

The measurement of the electrical parameters of the one-cell-module is shown in figure 5. We measure a fill factor (*FF*) decrease of < 1.5 % and a power loss < 2 % compared to initially measured values. The analysis of the electrical behavior shows no critical decrease of the relevant parameters (relative measurement uncertainties: V_{OC}: 1.5 %, I_{SC}: 2.0 %, P_{MPP}: 3.5 %, *FF*: 3.0 %). The one-cell reference-module containing an identical solar cell conventionally interconnected by soldering three ribbons on both sides shows a similar behavior.

It can be assumed that the more wave-shaped wires are used for the interconnection the better is the long-term stability due to the redundancy of the current paths. By increasing the width of the outermost contact fingers the reliability of the interconnection based on wave-shaped wires on contact fingers can be further improved.

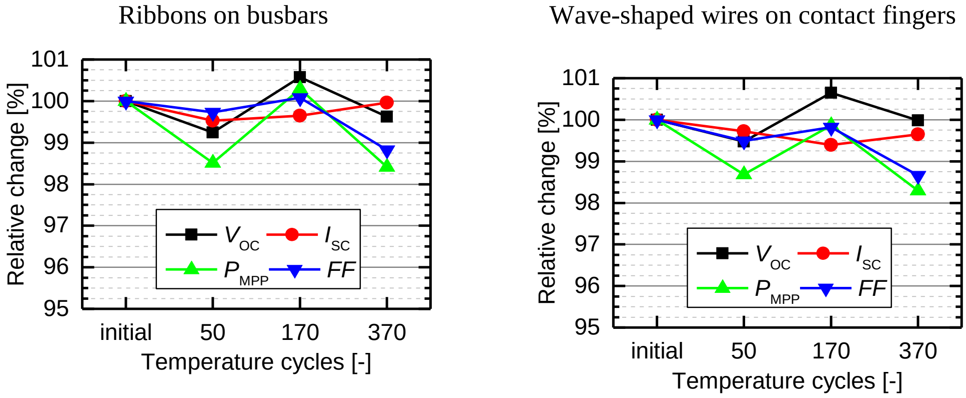

Fig. 5. Normalized measurement results of the electrical characterization of a standard solar cell connected with standard ribbons (left) and with six wave-shaped wires on both sides (right). Shown are changes of the most important electrical characteristics after the lamination process (initial) as well as after three temperature cycling periods (relative measurement uncertainties: V_{OC}: 1.5 %, I_{SC}: 2.0 %, P_{MPP}: 3.5 %, FF: 3.0 %).

4. Conclusion

In this work we demonstrate that the use of wave-shaped wires enables the interconnection of solar cells without busbars or contact pads directly on the fingers with a standard Sn62Pb36Ag2 solder. We show that the yield point of a round copper wire can be reduced by 90 % thus substantially reducing the thermomechanical cell stress. The EL images and the measurement of the electrical parameters of a one-cell-module show a power degradation of < 2 % as well as a fill factor decrease of < 1.5 % after TC 370. This is comparable to a one-cell reference-module based on three busbar interconnection and demonstrates the good reliability of a solar cell interconnected with wave-shaped wires soldered directly on the contact fingers. In addition wave-shaped wires will show advantages for back-contact solar cells (i.e. MWT or IBC solar cells) since their interconnection of both polarities on the rear side usually causes large cell bowing due to the CTE mismatch of copper and silicon that can be reduced by a lower yield limit of the interconnector [11].

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