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IV MEASUREMENTS OF SHINGLE SOLAR CELLS

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ABSTRACT:

Due to the large variety of contacting probes, the measured *IV* characteristics of solar cells differ considerably depending on the contacting used. In particular, the *FF* heavily depends on the selected contacting layout. The number and distribution of the contact points on the cell but also the shading by the measuring probes affect the *FF*. To be able to determine losses due to the cutting process from host to shingle cell and cell to module losses, the impact of two different contact units installed in an inline cell tester was evaluated. With PCBTOUCH contacting, the resistance losses of the front wires must be considered, otherwise the *FF* losses caused by cutting will be underestimated by $0.5\%_{abs}$. because the resistance contribution of the wires in the host cell measurement is significantly stronger than in the shingle cell measurement. For the universal contact probes, series resistance losses caused by the probes must also be corrected, but these do not affect the *FF* losses due to the cutting process, but only the absolute value of the *FF*.

Keywords: *IV* measurement, shingle solar cells, contacting units, fill factor losses

1 INTRODUCTION

Shingle cell modules are a promising concept for integrated PV applications with strong area limitations and high aesthetic requirements, such as vehicle-integrated PV. An efficient development of shingle-specific cell process steps such as wafer-cutting and edge passivation requires a current-voltage (*IV)* measurement of individual shingle cells to be able to evaluate the positive or negative effects of the measures carried out. Compared to full-size solar cells, the *IV* measurements of shingle cells have some challenging boundary conditions that need to be considered. For example, the individual shingle cells on the host cells are not electrically connected to each other with grid fingers, which can lead to inhomogeneities in the voltage distribution on the cell if the cable resistances vary. Due to their small area, the shingle cells are also particularly sensitive to shadowing by the measuring probes, which makes precise alignment of the cells in the measuring chamber necessary. To be able to measure shingle cells precisely, the inline cell tester at Fraunhofer ISE was upgraded so that shingle cells can be automatically unloaded from a box, aligned and contacted in the measuring station and after the measurement sorted into one of six BIN classes (Figure 1).

Figure 1: Shingle cells during magazine unloading. The blowing nozzles, which allow the cells to be separated in the magazine, are located to the right and left of the cell stack.

2 AIM AND APPROACH

In industrial production, the *IV* characteristics of individual shingle cells are usually not measured and sorted after they have been separated. However, for process development and optimization of individual process steps, such as cutting or edge passivation, an *IV* measurement of individual shingle cells is essential to be able to evaluate the positive or negative effects of the measures carried out. Since the contacting of the solar cells is not standardized, there is a variety of options for contacting the host wafers and shingle cells [1]. The differences in the *IV* parameters and electroluminescence (EL) images for the different contacting configurations for host and shingle cells are evaluated in this work and the advantages and disadvantages for the different contacting units are pointed out.

2.1 Challenges in correct solar cell contacting

2.1.1 PCBTOUCH

During the measurement with production PCBTOUCH, which is based on GridTOUCH technology [2] , 30 load- and 5 sense wires are pressed onto the cell from above, while the cell is also contacted from the bottom with 30 load and 5 sense contact tracks located on a printed-circuit board (pcb). Solar cells without busbars can also be contacted with the PCBTOUCH unit. Due to the large number of load wires and the resulting small distance of approx. 5 mm between the wires, the finger resistance of the cell is almost negligible. However, the situation is different with the resistance of the wires on the front. Since these are kept thin with a diameter of 0.3 mm to minimize shading of the solar cell, there is a significant voltage drop along the wires. With the 4-wire measurement, the wire resistances are compensated from the source-measure unit up to the edge of the cell. On the cell, however, the load and sense wires are electrically connected by the cell's grid fingers and a voltage gradient occurs across the cell. This shows that the resistance of the wires is included in the measurement. The voltage curve for a section of a cell is shown below the EL image in Figure 2. To make the effect clearly visible, the PCBTOUCH wires were only connected on the right side, by disconnecting the plug on the left side, whereas they are connected on both sides in standard configuration. Since an external voltage is applied to the cell during the EL measurement, the voltage on the right side of the cell is approx. 16 mV higher than on the left side for this measurement with a current of 10 A applied to the M2-sized solar cell. During the *IV* measurement, with current flowing out of the cell, the terminal would be on the side with the lower voltage.

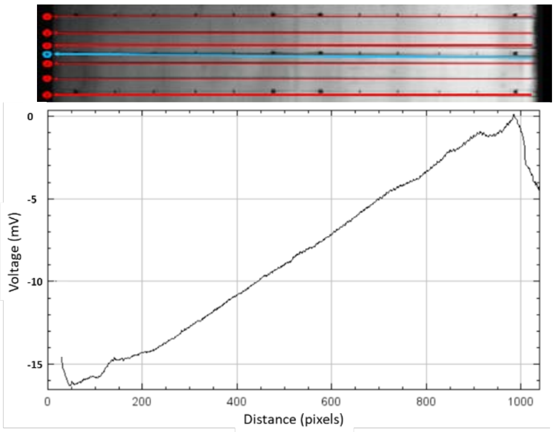

Figure 2: Top: EL image section of a solar cell that is contacted with the PCBTOUCH. The wires are only connected on the right side. Bottom: The voltage gradient was calculated from the grey value gradient of the EL image.

In production, the current and voltage connection on the PCBTOUCH takes place at both ends of the wires, which is equivalent to a parallel connection. The distance over which the current flows through the wires is halved so that the voltage drop across the cell is only a quarter as large as in the example shown above.

On the EL image in Figure 3 it is clearly visible that there is a higher gray value, and therefore a higher cell voltage between the load wires in which a sense wire runs over the cell. Since there is no current output via the sense wires from the measuring device during the EL measurement, the current must flow from the load wires via the busbars on the edge into the sense wires.

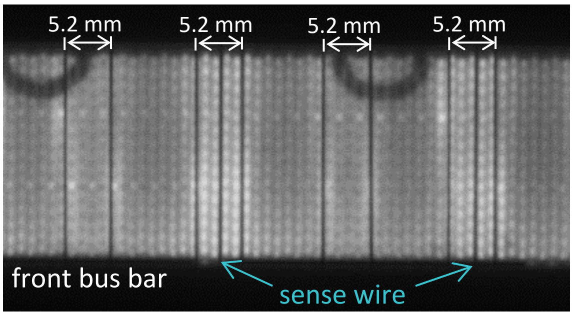

Figure 3: EL image of a shingle cell at a current of 10 A, which is 6 times I_{MPP} and clearly shows the series resistance effects.

Nevertheless, a correction of the wire resistance is necessary for a correct voltage measurement. As can be seen from the relevant literature [3], not the full series resistance of the wire is effective, but only one third of the resistance, because the current density to the external contacts increases continuously during an *IV* measurement. The resistance of the wires R_{wire} is calculated with:

$$R_{wire} = \frac{1}{3 \cdot n_{wire} \cdot n_{connection}} \cdot \rho_{wire} \cdot \frac{l_{wire}}{A_{wire}} \quad (1)$$

n_{wire} is the number of wires, $n_{connection}$ is the number of connection lines, l_{wire} is the length of the wires on the cell in which the current flows in direction of the connections. A_{wire} is the cross-section of the wire, which in case of the PCBTOUCH is 0.0707 mm² with a diameter of 0.3 mm. The specific resistance of a wire is 0.0792 Ω mm²/m and was determined using a 4-wire measurement on one wire with a length of 30 cm.

Since busbars or fingers on the cell that run parallel to the wires also contribute to the current transport and reduce the series resistance loss of the wires, their resistance R_{met} must also be considered when correcting the series resistance R_{wire} of the wires calculating the total resistance $R_{wire,cor}$ according to the formula of parallel interconnected ohmic resistances:

$$R_{wire,cor} = \frac{R_{wire} \cdot R_{met}}{R_{wire} + R_{met}} \quad (2)$$

Furthermore, care must be taken to ensure homogeneous contacting. The PCBTOUCH is equipped with 5 sense wires and each of the sense wires is surrounded by 6 parallel load wires. This leads to an asymmetric contacting when contacting host cells with 6 shingle cells. Since the individual shingle cells are not connected with each other via the metallization, the individual shingle solar cells are at different voltage potentials during the *IV* measurement, which can be clearly seen in the EL image in Figure 4 (top). The edge shingles are contacted with one less wire. This leads to an incorrect *FF* measurement. Contacting the host cells perpendicular to the busbars, which ensure an equipotential voltage distribution, is significantly more homogeneous as shown in Figure 4 (bottom).

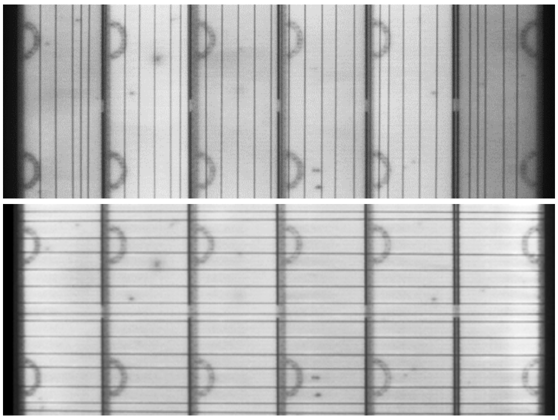

Figure 4: Sections of EL images of a section of the host cell ID 798 with 6 shingles contacted perpendicular to the fingers (top) and perpendicular to the busbars (bottom). The voltage distribution across the cell is significantly more homogeneous when contacting perpendicular to the busbars.

2.1.2 Universal contact probes (ucp)

With universal contact probes (ucp) [4], solar cells can also be contacted independently of the presence or location of busbars. This contacting scheme was used for the following experiments and the host and shingle cells were contacted in the center perpendicular to the fingers (Figure 5). With the ucp, the voltage measurement does not take place on the cell, but in the middle of the contact strip. As a result, the contact resistance between the ucp and the metallization of the cell and the line resistance of the ucp are included in the measurement. In addition, the shading of one probe, which has a shading width of approx. 5 mm and thus covers approx. 15% of the active shingle cell area, reduces the *FF*. To compensate the shading and to illuminate the unshaded part of the cell at 1000 W/m² (related to the whole cell area), the flash power must be increased, which leads to higher currents in the unshaded part of the cell and thus leads to higher series resistances in the grid fingers. For one strip, halm determined the additional series resistance contribution of 1.3 mΩ for PERC cells [5]. This value was used for the corrections in the experiments carried out.

When measuring host cells, clear signal fluctuations between the individual shingle cells have been observed in the EL image of solar cells contacted with ucp (Figure 5, top). Since the individual shingle cells are not electrically connected to each other via grid fingers and the contact strips are connected pairwise with individual cables to the measuring electronics, no compensating currents can flow between the contact strips. Slight differences in the cable resistances of the measuring stripes lead to uneven voltage distribution during the measurement. In this case, limiting resistors in the individual cables improved the homogeneity (Figure 5, bottom).

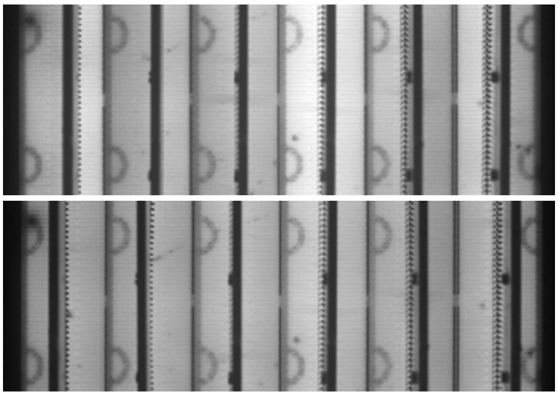

Figure 5: The upper EL image section of a M6 host cell shows clear signal fluctuations between the individual shingle cells. In the lower image, limiting resistors in the individual leads have improved the signal homogeneity.

2.1.4 Correction of the *FF* for comparability of the measurements with different contacting units

Since the current paths differ depending on the contact layout used, the finger resistance must be considered when comparing the results obtained with PCBTOUCH and ucp [6]:

$$\Delta FF = \frac{1}{12} \cdot \frac{{I_{mpp}}^2}{I_{sc} \cdot V_{oc}} \cdot GridRes \cdot N_{cont,1} \cdot \left(\frac{1}{{N_{cont,1}}^2} - \frac{1}{{N_{cont,2}}^2} \right) \quad (3)$$

$N_{cont,1}$ corresponds to the number of contact strips or wires of the measuring setup. $N_{cont,2}$ is the number of contacts to convert to. For the complete compensation of the finger resistances, $N_{cont,2} = \infty$ should be chosen. *GridRes* is the grid resistance between the contacts.

3 EXPERIMENTAL

3.1 Impact of the number of shingle cells on the *IV* measurements

In this experiment, it shall be shown that the influence of the series resistance of the PCBTOUCH wires is not negligible, and a correction of the wire resistance is necessary for the comparability of measurements on host and shingle cells based on different contact units.

Five shingle cells were used for the measurements, which have almost identical *IV* characteristics in the individual measurements.

In the first series of measurements, one shingle cell was measured first and then the number of separated shingle cells measured in parallel was increased to five. The cells were contacted with 20 load and 5 sense wires perpendicular to the busbar (Figure 6, top). In the second variant, the cells were contacted with 30 load and 5 sense wires perpendicular to the fingers. In this configuration, the fingers run longitudinally across the cell (Figure 6, bottom). In addition, in a series of measurements with these cells, the current and voltage terminals were only connected on one side of the wires.

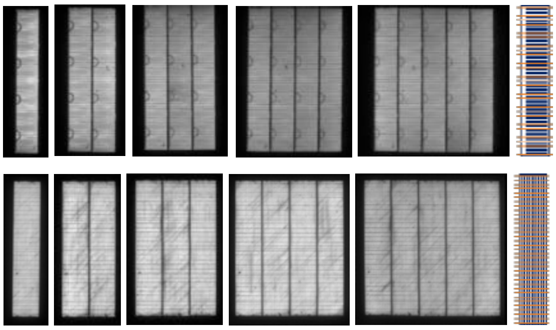

Figure 6: EL images of shingle cells with 25 wires running perpendicular to the busbars (top) and shingle cells with 35 wires running perpendicular to the fingers (bottom) during *IV* measurement. A contacting scheme is shown on the right side.

3.2 Determination of the due to the process for shingle separation

For *IV* measurements of 20 host cells, the Pasan PCBTOUCH unit with 30 load wires was used for contacting the cells perpendicular to the busbars. Furthermore, the halm ucp were used for central contacting each of the shingle cells of the host wafer in the middle perpendicular to the contact fingers.

After the measurement, some of the cells were separated using laser scribe and mechanical cleave (LSMC), the second part was separated using thermal laser separation (TLS). After cutting the measurements on 30 shingle cells are carried out with PCBTOUCH and ucp, respectively (Figure 7).

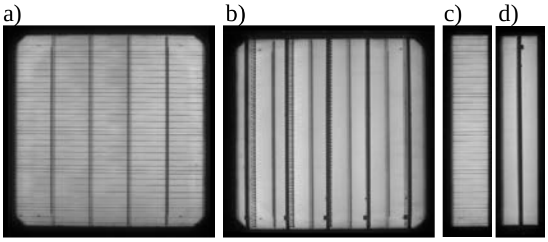

Figure 7: The EL images of (a-b) the M2 host cells and (c-d) the 1/5 shingle cells show the impact of contacting units. The host cells were contacted with (a) the PCBTOUCH unit perpendicular to the busbars and (b) the ucp stripes in the center of each of the shingle cells. The shingle cells were contacted using (c) the PCBTOUCH perpendicular to the busbar with 35 wires and (d) a centrally arranged ucp.

4 RESULTS

4.1 Impact of the number of shingle cells on the *IV* measurements

For all contacting configurations, the *FF* decreases with an increasing number of shingle cells measured in parallel (open symbols in Figure 8), although a constant *FF* would be expected. In the case of single-sided connection of the current and voltage wires, the drop in the *FF* is about 2% (abs.), i.e., a factor of 4 higher compared to the configuration with wires connected on both sides. If the series resistance contribution of the wires is corrected according to formula (1), the *FF* does not change with an increasing number of cells measured in parallel. In the case of the wires running perpendicular to the busbars, the resistance of the grid fingers was also considered.

Since the grid resistance $R_{met} = 5.42$ mΩ/cm is relatively high compared to the wire resistance $R_{wire} = 0.224$ mΩ/cm, the correction resistance $R_{wire,cor}$ is only 4% smaller than R_{wire}.

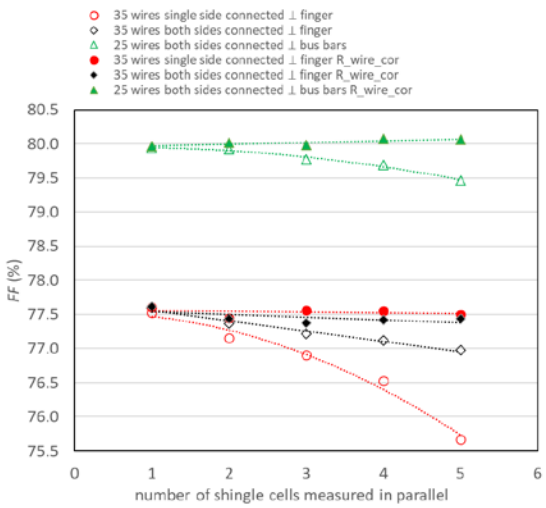

Figure 8: The measured *FF*s decrease in all test variants of contact configurations (see legend) with an increasing number of shingle cells measured in parallel (open symbols). If the series resistance contribution of the PCBTOUCH wires is considered (filled symbols), the *FF* remains almost at the same level with varying number of shingle cells measured in parallel.

Measuring perpendicular to the busbars with 25 wires as well as perpendicular to the fingers with one- and two-sided connection, the deviation of the corrected *FF* is below 0.1%$_{rel.}$ and thus in the range of measurement uncertainty for PCBTOUCH measurements.

This experiment confirms that the resistance of the PCBTOUCH wires has a significant impact on the *FF* determination of the cells and must be considered when comparing cells of different sizes. The conductivity of the backside PCB contact is high enough and does not have a significant influence on the *FF*.

4.2 Determination of the losses due to the process for shingle separation

*J*sc differences between the host cells and separated shingle cells due to differences in the contacting units used can be minimized by an appropriate calibration of the measuring system by compensating different amounts of contact-probe-induced shading with an increased intensity of the measuring light. Remaining deviations in J_{sc}, which were less than 0.2 mA/cm² in all cases, were corrected in this experiment so that the J_{sc} mean value for each group is 39.7 mA/cm² and J_{SC} influence on the η is eliminated. Since no power is extracted from the cell under the U_{oc} conditions, U_{oc} measurements are not affected by series resistance losses. Note that U_{oc} deviations were negligible in this experiment. However, this is different with the *FF* determination (Figure 9). Without wire resistance correction, the PCBTOUCH measurements underestimate the *FF* loss of apparently 1.6%$_{abs.}$ due to the TLS cutting process by 0.5%$_{abs}$. Taking the wire resistance correction into account, the *FF* losses of 2.1%$_{abs.}$ determined with the PCBTOUCH unit are close to the *FF* losses of 1.9% determined with the ucp unit. In contrast to the PCBTOUCH, the *FF* losses determined with the ucp unit remain the same with and without resistance corrections, but the absolute *FF* level before and after shingle separation changes. If both the PCBTOUCH and ucp measurements are converted to the grid finger resistance free (and hence comparable) situation, ucp and PCBTOUCH results are at the same *FF* level.

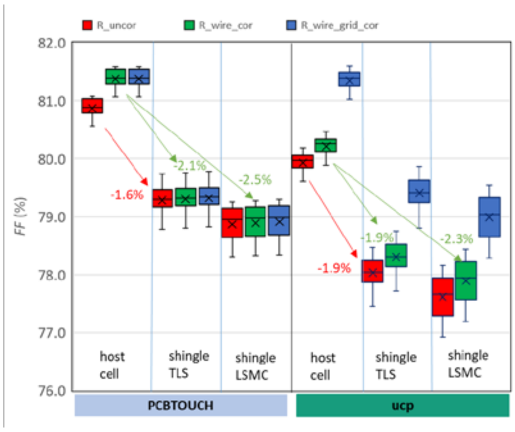

Figure 9: *IV* parameters of the host and shingle cells measured with (left) the PCBTOUCH unit and (right) the universal contact probes (ucp).

This is also reflected in the efficiency, which only differs in the 2nd decimal digit if the finger resistance is neglected. With both contact units, a 0.4% higher *FF* loss is determined for the LSMC process compared to the TLS process.

Table 1: Cell efficiencies η of host and shingle cells only wire corrected $R_{\_wire\_cor}$ and wire and grid resistance corrected $R_{\_wire\_grid\_cor}$.

η (%)	Host	Shingle TLS	Shingle LSMC
PCBT $R_{\_wire\_cor}$	21.94	21.30	21.16
ucp $R_{\_wire\_cor}$	21.63	21.01	20.88
PCBT $R_{\_wire\_grid\_cor}$	21.94	21.30	21.16
ucp $R_{\_wire\_grid\_cor}$	21.92	21.30	21.17

4 CONCLUSIONS

To determine the cutting losses from shingle host cells to separated shingle cells precisely, both, the PCBTOUCH and the ucp unit, are suitable for contacting the solar cells. With PCBTOUCH contacting, the resistance losses of the front wires must be considered, otherwise the *FF* losses caused by cutting will be underestimated by $0.5\%_{abs}$ for the present situation. Series resistance losses must also be corrected for the ucp, but these do not affect the *FF* losses before and after cutting, but only the absolute value of the *FF* in both states. The *FF* losses determined with both contacting units differ by $0.2\%_{abs}$. Taking the series resistance of the cell´s contact fingers into account, the contacting-unit-induced differences in the *FF* and η become smaller than the measurement uncertainty.
The wire resistance correction method presented shows good results for the samples investigated. The load and sense wires are effectively shorted, which is important for the validity of the correction. The general case without short circuit of the wires is more complex though and the correction becomes more difficult.

5 ACKNOWLEDGMENTS

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