CONTACTING OF BUSBARLESS SOLAR CELLS FOR ACCURATE *I-V* MEASUREMENTS

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ABSTRACT: In recent years, solar cell development has undergone a major change in metallization layout. In their most radical form, busbarless solar cells completely omit the busbar and leave the fingers as solely contacting area. Consequently, characterization and calibration laboratories were forced to develop new contacting units. At the same time, the question of the correct arrangement of current and sense contacts arises. To perform accurate and precise measurements of the current-voltage characteristic of busbarless solar cells, we transfer the well-established concept of *busbar-resistance neglecting* contacting to the measurement of busbarless cells. The result is a universally valid *grid-resistance neglecting* contacting scheme, which provides the same fill factor as one would get if one had contacted the entire metallized area of the solar cell. We demonstrate that a variety of contacting schemes are able to determine this fill factor if the sensing contact is correctly placed. We provide experimental evidence of consistent results for a contacting with 12 contact bars at ISFH CalTeC and 30 wires at Fraunhofer ISE CalLab, respectively. For the fill factor of 15 silicon solar cells with finger line resistances ranging from 0.6 to 12 Ω/cm we show that the E_n-values between both calibration laboratories are well below 1, demonstrating a very good agreement within the accompanied measurement uncertainty.
Keywords: solar cell, busbarless, fill factor, contacting, *I-V* measurement

1 INTRODUCTION

A major goal of solar cell development in recent years was to reduce the amount of silver that is required for module interconnection by soldering. This development led to busbarless solar cells in which fingers are no longer cross-connected via busbars. Instead, the contacting of the individual fingers takes place during module production [1]. Measuring the current-voltage characteristics of busbarless cells before module integration is a necessity for comparing the cell process independent of the module fabrication. For this a non-permanent and non-destructive approach to electrically contact each grid finger is required.

No explicit standard exists for the design of solar cell contacting units. Some authors [2, 3] demand a contacting method which reflects the module integration, while others [4, 5, 6, 7] favor to contact the solar cell so that the same results are obtained in different laboratories using different contacting schemes. For the measurement of conventional (H-pattern) solar cells with busbars, the generally accepted concept is an infinite number of contact points on the busbar (“ideal” contacting), thus neglecting its resistivity. A current-voltage (*I-V*) characteristic that would be measured with such a *busbar-resistance neglecting* (brn) contacting has a fill factor FF_{brn}. However, having only finite number of contacts, it was shown [4, 6] that a specific positioning of the voltage measuring contact (sense contact) allows to approximate this contacting scheme and thereby provides FF_{brn}. In this work, we transfer this principle concept to the measurement of busbarless solar cells by implementing *grid-resistance neglecting* contacting schemes. Since the related *I-V* data is free of resistance limitations from the grid metallization, the corresponding fill factor is named FF_{grn}.

The decisive advantage of this approach is that it can be achieved with different technical contacting solutions and thus allows the comparison of measurement data from different laboratories using different contacting units. In addition, using cell-to-module (CTM) analysis, it allows for a general approach to transfer the determined FF_{brn}/FF_{grn}—value to the *FF*-value, which best reflects the final contacting in the module. Please note that such a CTM analysis has to be performed anyway for the short circuit current I_{sc} and the open circuit voltage V_{oc} to take into account the optical conditions in the module as well as its operating temperature. Therefore, we expressly point out that this *grid-resistance neglecting* contacting scheme determines an upper limit of the performance of the respective solar cell, but not necessarily its performance in a module.

By means of analytical modelling, we study the impact of the number of contacting bars/wires on the fill factor of current-voltage curve measurements of busbarless solar cells with different finger resistivity. To verify this experimentally, we compare the results obtained from contacting 15 solar cells with grid resistances between 6 and 120 mΩ/cm using a 12 contact bar and a 30 wire contacting unit. We focus on comparing fill factor values since this value is most sensitive to the contacting scheme.

2 CONTACTING BUSBARLESS SOLAR CELLS

2.1 Technical solutions

So far, two generally different approaches for contacting the front surface of busbarless solar cells do exist. While one solution uses wires stretched over a slightly curved surface on which the solar cell is positioned [8], all other approaches are based on contacting bars [9, 10, 11]. The advantage of the wire-based approach is a relatively low shaded area percentage that is reached by using thin wires. In addition, the use of about 30 current-carrying wires results in a contact pattern that is relatively insusceptible to finger interruptions. In contrast, the most important advantage of the contact bars is their compatibility with existing contacting units.

The positioning of the voltage sensing contact is handled quite differently. While in some cases current and voltage contacts are both realized on the metal grid of the solar cells, the sensing is performed directly at the current carrying probe bars in other cases. Since both, the position of the sense contact and the number of current-carrying contacts influence the fill factor of the measured *I-V* curve, and this influence increases significantly with increasing grid resistance [12], the results obtained with the different contacting units are not necessarily consistent.

At ISFH CalTeC the contacting is performed by contacting bars developed and manufactured by pv-tools for ISFH. Figure 1a shows a photograph of the contacting bars. The bars consist of a gold-plated foil wrapped around an elastic core and have a maximum thickness of 1.5 mm. 12 bars are positioned equally spaced and carry approximately the same current. As shown in Fig. 1b, electroluminescence (EL) imaging demonstrates a very homogeneous contact of the whole cell. Two wires making contact to the solar cell by magnets positioned in the underlying chuck realize voltage sensing. The sensing wires are positioned at 1/5th of the distance of the two contacting bars at bar 4 and 8.

The contacting solution used at Fraunhofer ISE CalLab is an in-house development based on the wire contacting technology of Pasan SA. As shown in Fig. 2, it consists of 30 equidistant current and 5 additional voltage-sensing wires.

a)

b)

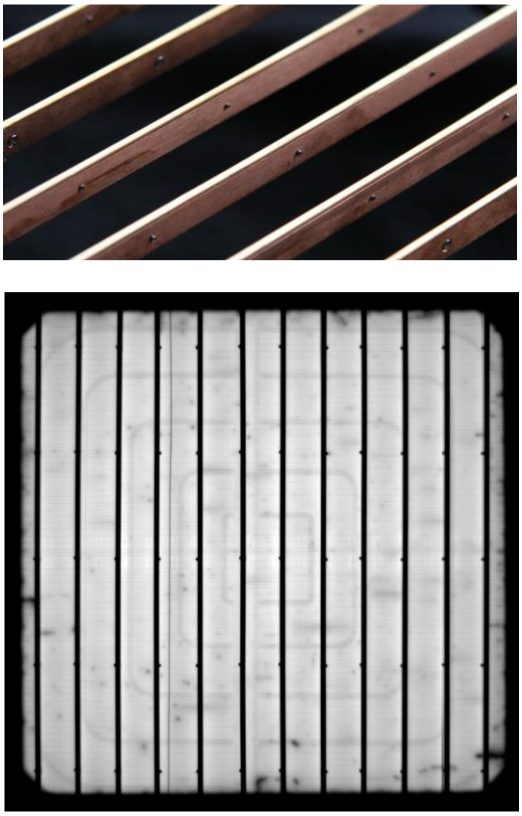

Figure 1: a) Elastic contacting bars from pv-tools developed with and manufactured for ISFH b) EL image of a busbarless solar cell demonstrating homogenous contacting of all fingers. One voltage sensing wire is used next to the fourth contacting bar counting from the left. Please note that the darker ring-like structure corresponds to the vacuum channels in der chuck. These become visible due to the bifaciality of the cell. In the area of the channels, the reflection is reduced and therefore the luminescence signal is lower.

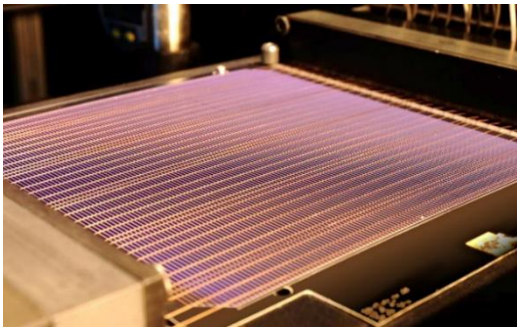

Figure 2: Wire contacting unit at Fraunhofer ISE CalLab using 30 equidistant wires and 5 additional voltage-sensing wires.

2.2 The grid resistance neglecting contacting scheme

For the measurement of the *I-V* curve of conventional solar cells with busbars, a generally accepted contacting concept is the *busbar-resistance neglecting* contacting scheme. This is achieved with an infinite number of contact points on the busbar or by using smart sensing concepts [4-7] that position the sense contacts at a defined distance to the current contact. Such a contacting scheme results in *I-V* curves – and especially *FF*-values - free of series resistance effects of the busbar.

The equivalent approach for busbarless solar cells is a *grid-resistance neglecting* contacting scheme. Generally, this would require the entire metallized area of the solar cell to be contacted. Since this is hardly feasible, the question arises whether a smart sensing concept together with a finite number of contact points also allows a grid-resistance neglecting measurement of the solar cells *I-V* characteristics.

To answer this question we model the solar cell analytically along one finger. We use a one-dimensional network of two-diode models interconnected by series resistors representing the finger line resistance R_l; see Fig. 3 for a sketch of this model.

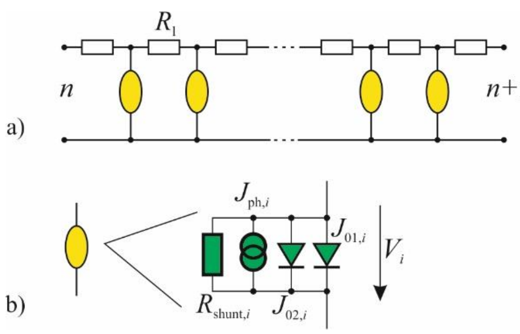

Figure 3: Schematic of the diode network model. Each finger is divided into small elements (a) where each element is represented by a two-diode model and is (b) connected to the next neighboring elements with a series resistor corresponding to the finger line resistance.

The parameters of each two-diode model are: J_{ph} = 40 mA/cm², J_{01} = 60 fA/cm², J_{02} = 0.50 nA/cm², R_{sh} = 1E+9 Ωcm², giving a *FF* of 84.50 %, a J_{MPP} of 38.29 mA/cm² and a V_{MPP} of 617.2 mV. For the simulations in the next two sections we vary the number of contact points per finger and the finger line resistance. We numerically solve for the voltage distribution over the finger for half the distance between two contacting points obtained from contacting bars or wires positioned perpendicular to the fingers.

2.3 Voltage distribution and ideal sensing position

We simulate six different wire/bar configurations with 6, 9, 12, 20, 30 and infinite wires/bars. Please note that the wires/bars are assumed to be transparent to not affect I_{sc} and V_{oc}. We set the finger resistance to 5 Ω/cm with a finger pitch of 1.96 mm (corresponding to 80 fingers on the cell). The resulting voltage distributions are shown in Fig. 4 as a function of the relative distance between two adjacent wires/bars. The voltage distributions are approximately parabolic and intersect the voltage distribution with an infinite number of wires (∞-wires), at about 22 % of the distance of two adjacent contacting wires or bars. In order to perform a *grid-resistance neglecting* measurement, the voltage sensing contact need to be placed at this position. Doing so, the corresponding fill factor (not shown) is 0.16 % lower for 6 wires, 0.02% lower for 9 wires and agrees within 0.01% for 12, 20 and 30 wires to FF_{grn}.

The red line, corresponding to 6 wires, intersects the black reference line at a different position. The reason is that the height of the potential distribution is already so large that the points along the finger operate at working points considerably different from the maximum power point.

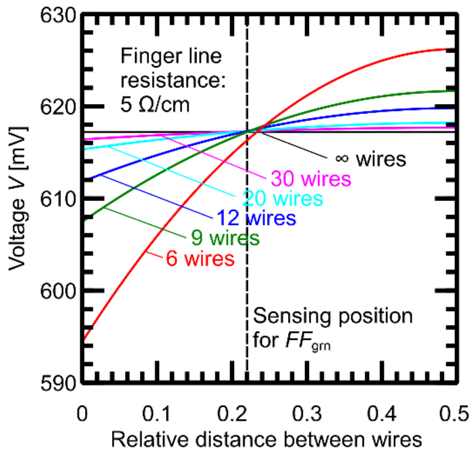

Figure 4: Voltage distribution over one finger for different numbers of contacting bars/wires, a finger resistance of 5 Ω/cm and a current extraction of J_{MPP} = 38.29 mA/cm² for all cases.

A simplified consideration confirms this value. It is assumed that the current I flowing into each small finger element is constant, i.e. does not depend on the position x of the finger. The voltage distribution, resulting from the current flowing within the finger with line resistance R_l then follows a parabolic shape described by the differential equation $V''(x) = -IR_l$. Introducing the normalized length $s = x/d$ with d being the distance between two contact bars (cb) or wires, we end up with the differential equation $V''(s) = -IR_l d^2$. With the boundary conditions $V(0) = V(1) = V_{cb}$ (V_{cb}: voltage at the contact bars) and $V'(1/2) = 0$ we obtain the solution $V(s) = V_{cb} + \frac{1}{2} IR_l d^2 (s - s^2)$. Assuming further, that the representative voltage of a solar cell is the mean solar cell voltage, the voltage sensing position for FF_{grn} follows as the position where the voltage distribution is equal to its mean value. Since the mean of $(s - s^2)$ between $s = 0$ and 0.5 is 1/6, we end up with a sensing position of $s = 0.21$. For such a simplified consideration, the agreement with the 0.22 from the numerical study above is surprisingly good.

2.4 Impact of finger resistance and uncertainty of sensing position

By means of numerical simulations, we analyze the 12 bar/wire configuration introduced above in more detail for a range of finger resistances between 2 and 20 Ω/cm. We further analyze the *FF*-deviation for an uncertainty of ±0.5 mm and ±1 mm in the positioning of the voltage sensing contact.

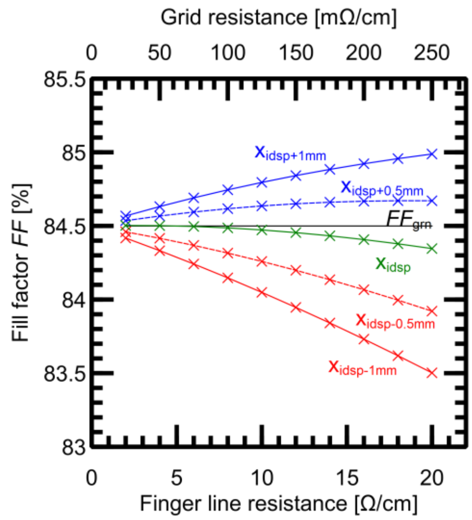

Figure 5: Fill factors for 12 bar/wire configuration on an M2 solar cell obtained with sensing at the ideal sensing position x_{idsp} at 22 % of the distance of adjacent contact bars/wires (green) and plus and minus 1 mm from the ideal sensing position (blue and red, respectively).

As shown in Fig. 5, the 12 bar configuration yields *FF*-values close to FF_{grn} with a maximum deviation of 0.2 %. This holds for high finger line resistances up to 20 Ω/cm (grid resistance 250 mΩ/cm) provided that the voltage sensing contact is at 22 % (corresponding to 2.86 mm for an M2 cell measured with 12 contact bars) of the distance of two adjacent current carrying contact bars/wires (green curve). The reason for the deviation from FF_{grn} at high finger line resistances is the same as discussed above. The greater the finger line resistance, the higher the potential distribution. Thus along the finger, the solar cell operates at working points that deviate considerably from the maximum power point. Consequently, the fill factor starts to deviate.

Figure 5 also shows the sensitivity of the *FF* on the sensing position. A misplacement of ±1 mm translates to 0.2 % *FF*-deviation for 4 Ω/cm finger line resistance (grid resistance 50 mΩ/cm) and 0.8 % for 16 Ω/cm finger line resistance (grid resistance 200 mΩ/cm). For ±0.5 mm misplacement in the sensing position, the respective *FF*-deviations are 0.1 and 0.5 %. With an increasing finger line resistance, the height of the potential distribution increases and the associated increase of the gradient at the sensing position leads to an increasing sensitivity of the voltage measurement from the position of the voltage sensing contact.

3 EXPERIMENTAL VERIFICATION

In order to gain confidence that the predictions of the numerical simulations provide reasonable results, we verify them experimentally for two busbarless solar cells in the M2 format with significantly different finger resistances of 1.6 and 9.6 Ω/cm, respectively. We increase the distance between the sensing wire and the current carrying contacting bar step by step and measure the current-voltage curve under illumination. Fig. 6 shows the fill factor values of these curves together with the predictions of our numerical simulation. Within the experimental uncertainties, measured and simulated values match.

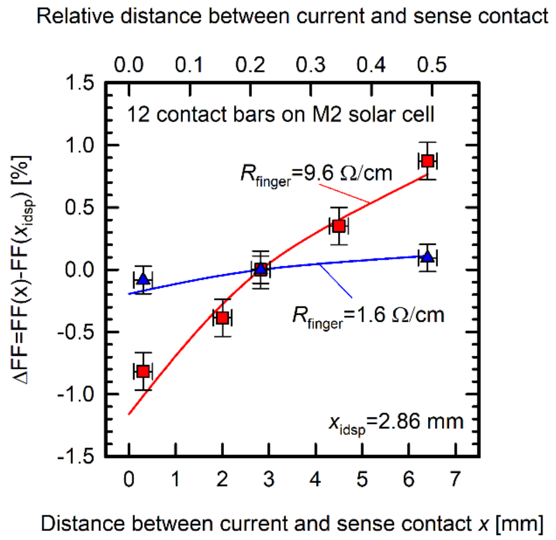

Figure 6: Deviation of the fill factors relative to the value obtained at the ideal sensing position x_{idsp} at 22 % of the distance between sensing wire and current contact bar (corresponding to 2.86 mm in this case). Experimentally determined values are shown as squares. Lines are results of corresponding numerical simulations.

Aiming at verifying the prediction that *I-V* measurements with 12 contact bars and 30 wires provide the same fill factor within the framework of their typical measurement uncertainties, we measure 15 busbarless solar cells with finger line resistances ranging from 0.6 to 12 Ω/cm at the two accredited calibration laboratories ISFH CalTeC and Fraunhofer ISE CalLab. The results are shown in Fig. 7. To decide whether the measurement results match, we use the E_n criteria [13, 14]. The E_n number is less than one if the measured values agree within their associated uncertainties and it is smaller the better the agreement is. If the E_n number is above one, there is no match, i.e. the respective uncertainty intervals no longer overlap. For each solar cell measured in this work, the E_n value is within 0.15 and 0.61 and thus well below one, indicating that both contacting schemes provide same FF_{grn} results within their measurement uncertainty.

4 SUMMARY

Our simulation shows that *grid-resistance neglecting* measurements of the *I-V* characteristics of busbarless solar cells are possible. The requirement is the application of a high number of contacting wires or the positioning of the sensing contact at 22 % of the distance of two adjacent contacting bars. The smaller the number of contacting bars/wires and the higher the grid resistance the larger the gradient of the potential near the ideal sensing position. Consequently, a misplacement of the voltage sensing contact results in a larger deviation of FF_{grn}.

For 12 contacting bars and an M2 solar cell, the ideal sense position of 22 % corresponds to a distance of 2.86 mm. In this case, the misplacement of the voltage sensing contact should not exceed -0.5 mm if we want to keep the deviation of the fill factor below -0.5%. This holds for finger line resistances of up to 20 Ω/cm. A misplacement resulting in a larger distance to the nearest current carrying contact should completely avoided preventing an overestimation of the fill factor and thus the energy conversion efficiency.

As shown by comparing the fill factor values of *I-V* measurements using 12 contacting bars and 30 wires respectively, both contacting schemes provide consistent results. This is demonstrated for 15 solar cells with finger line resistances ranging from 0.6 to 12 Ω/cm.

Finally, we highly recommend disclosing the used measurement configuration with every set of *I-V* data for transparency, credibility and a further CTM analysis.

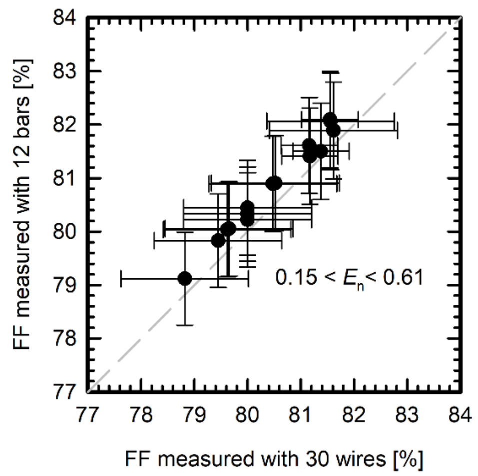

Figure 7: Fill factors FF_{grn} of 15 solar cells contacted with 30 current carrying wires at Fraunhofer ISE CalLab and with 12 current carrying contact bars at ISFH CalTeC. E_n-values well below 1 for all data points indicate consistent results within the accompanied uncertainties of the measured fill factors.

ACKNOWLEDGMENT

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