

# Impact of the contacting scheme on $I$ - $V$ measurements of metallization-free silicon heterojunction solar cells

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**Abstract.**  $I$ - $V$  measurements are sensitive to the number and positioning of current and voltage sensing contacts. For busbarless solar cells, measurement setups have been developed using current collection wires and separate voltage sense contacts. Placing the latter at a defined position enables a grid resistance neglecting measurement and thus  $I$ - $V$  characteristics independent from the contacting system. This technique has been developed for solar cells having a finger grid and good conductivity in the direction of the fingers. The optimal position of the sense contact in case of finger-free silicon heterojunction solar cells has not yet been studied. Here, the lateral charge carrier transport occurs in a transparent conductive oxide layer resulting in a higher lateral resistance. We perform finite difference method simulations of HJT solar cells without front metallization to investigate the impact of high lateral resistances on the  $I$ - $V$  measurement of solar cells. We show the high sensitivity on the number of used wires for contacting as well as the position of the sense contact for the voltage measurement. Using the simulations, we are able to explain the high difference of up to 7.5% in fill factor measurements of metal free solar cells with varying TCO sheet resistances between two measurement systems using different contacting setups. We propose a method to compensate for the contacting system to achieve a *grid-resistance neglecting* measurement with both systems allowing a reduction of the  $FF$  difference to below 1.5%.

**Keywords:** Heterojunction solar cell /  $I$ - $V$  measurement / contacting / fill factor / metal-grid free / module integration

## 1 Introduction

The high efficiency and bifaciality of silicon heterojunction solar cells (HJT) as well as their lean process flow results in an increased production capacity of this cell technology since the mid 2010s, although the average cost per module is still higher than most other technologies [1]. A high portion of the costs can be assigned to the silver consumption for the metallization on both sides of HJT cells using low-temperature silver pastes which are suffering from reduced conductivity compared to Ag pastes processed at high temperatures [2,3]. Therefore, reducing the amount of silver used for HJT solar cells, and in the photovoltaic sector overall, is a major goal in recent c-Si solar cell research [4]. The transparent conductive oxide (TCO) on the surface of heterojunction solar cells in

principle enables an operation without any metallization on cell level. The lateral charge carrier transport then occurs primarily in the TCO, but with a much higher series resistance compared to a metal grid. For module integration the cell interconnectors are directly contacted to the TCO, although the higher contact resistance of cell interconnects to the TCO as well as the higher sheet resistances of the TCO compared to a metal grid result in losses on module level [5,6]. Nevertheless, we estimate sheet resistances between 50  $\Omega/\text{sq}$  and 100  $\Omega/\text{sq}$  to be suitable for a module consisting of HJT solar cells without a metal grid. Here, we predict 25 to 30 wires for the interconnection of cells with M6 wafer size to achieve a performance with a fill factor in the range of 80% on module level. Omitting the metallization is also of high interest for perovskite/c-Si tandem solar cells featuring a TCO layer and having high requirements towards the metallization process [7].

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Measuring the current-voltage ( $I$ - $V$ ) characteristics of bare solar cells is crucial to compare solar cells and cell processes. It is also necessary for sorting the cells during manufacturing to have matching cells in a module. While many aspects of the measurement conditions are standardized, there is no international standard on the non-permanent and non-destructive contacting of the solar cells. Typically, separate contacts for current extraction and voltage sensing are used to ensure a four probe configuration and an independent measurement of the voltage and current characteristics. It has been shown, that the  $I$ - $V$  characteristics highly depend on the contacting procedure and the position of the contacts, especially the fill factor ( $FF$ ) and efficiency [8]. The general approach is to measure solar cells independently from the contacting procedure resulting in comparable measurement between different systems and is widely accepted [9–11].

For solar cells with busbars (BB) an infinite number of current points is used to contact the cell resulting in a *busbar-resistance neglecting (brn)*  $I$ - $V$  characteristic [12]. Having only a finite number of contacts leads to a voltage drop between two current extraction points due to the non-zero resistivity of the busbar. Using a smart positioning of the voltage sense contact allows to approximate the infinite number of current contacts and to measure the average voltage over the busbar [9].

Going from solar cells with busbars to busbarless cells, there are at least two different approaches to contact these cells using either elastic bars or wires stretched over a slightly bent solar cell. Both achieve a contact to all fingers of the cell. Comparable to the contacting of cells with busbars using a finite number of contacts, the finger resistivity results in a voltage drop between two current contacts. The gradient and height of this drop depends on the number of current contacts, and the resistivity of the fingers leading to a dependency of the measured voltage on the position the voltage sense contact.

Different approaches can be found in the literature on how to electrically contact bare solar cells. Some prefer a contacting comparable to the integration in the module [13,14]. The so-called *grid-resistance-including (gri)* method places the voltage sense contact in proximity to the current contacts representing the cell performance in a module [12]. Here, the measured fill factor and efficiency depend on the number of current contacts and the resistivity of the metal grid and measurements of two systems with different amount of current contacts can not easily be compared.

For the second approach a smart sensing concept is used to approximate the contacting of the full metal grid resulting in a measurement independent from the contacting system and the resistivity of the metal grid [11]. Here, the voltage sense contact is placed between two current extraction wires. Bothe et al. showed, that for a sufficiently high number of current wires the full contacting can be approximated by placing the sense contact at the same relative position of  $d_{sp} = 0.2$  between two current contacts, independently of the actual amount of current wires. This approach is called the *grid-resistance neglecting (grn)* method. They also showed the dependency on the specific resistivity of the metal grid. Measuring the fill factor is

highly sensitive to even small deviations from the ideal sense position and this sensitivity increases with rising finger line resistivity.

Omitting the metallization of heterojunction solar cells completely leads to a high increase in series resistance because the charge carrier transport occurs primarily in the TCO. Therefore, special care has to be taken for the non-permanent and non-destructive electrical contacting to measure the  $I$ - $V$  characteristics of the cells before module integration.

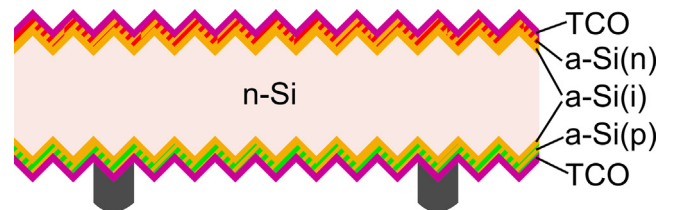
In this paper we simulate the  $I$ - $V$  measurement of HJT solar cells without metallization to test the approximation made by Bothe et al. for solar cells with finger metallization but without busbars, which allows to measure the same  $I$ - $V$  results independently from the contacting. The  $I$ - $V$  curve at several positions of the voltage sense contact between two current extraction wires/bars is simulated for various sheet resistances of the front TCO and number of wires used for contacting. The corresponding fill factors are extracted and compared against the quasi-full contacting case with an equipotential voltage over the whole cell area to find the position of the sense contact for the *grn* measurement of each parameter. The simulations are then compared to  $I$ - $V$  measurements of different cells with various sheet resistances. The measurements are performed with two different measurement systems. We show the high dependency of fill factor and efficiency measurements on the position of the voltage sense contact for solar cells with high lateral resistance. Afterwards we discuss appropriate measurement procedures for such cells.

## 2 Methods

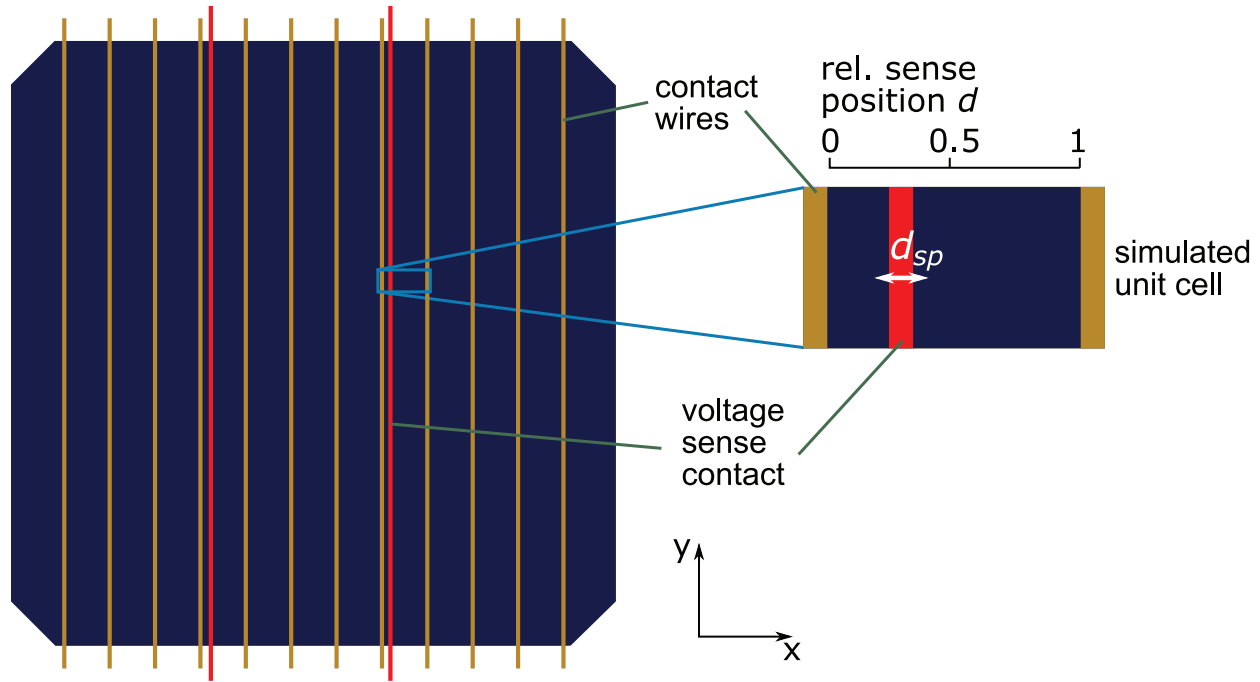
### 2.1 Simulations

We simulate the measurement of HJT solar cells without metallization with the commercially available tool *Quokka3* using finite difference method (FDM) simulations to find the optimal positioning of the voltage sense contact. For various sheet resistances of the TCO as well as different wire/bar configurations of the contacting setup we simulate the  $I$ - $V$  curve of the respective cell.

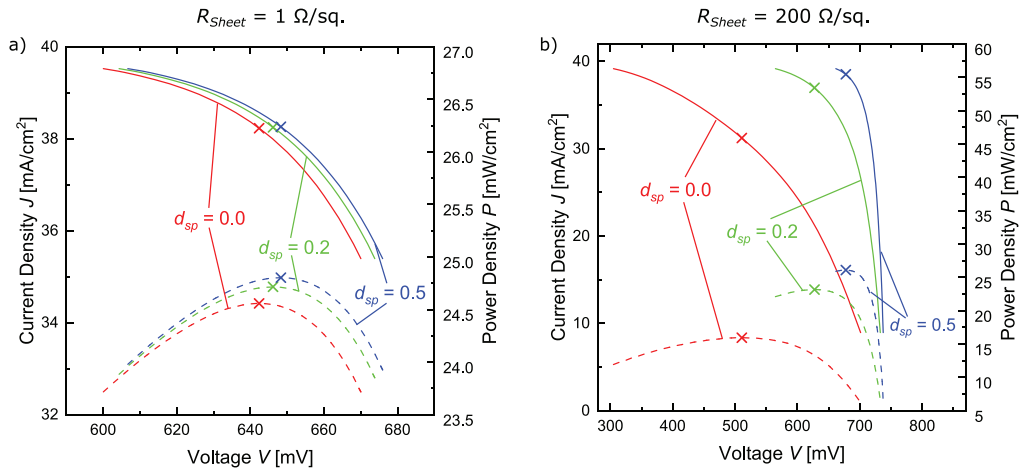
A schematic cross section of the simulated cell is shown in Figure 1. The bulk is covered on both sides with a skin layer where the amorphous layers are combined with the TCO. To simulate only the electrical effects, the skin layers are set to be fully transparent. The front side is contacted by structures representing the current extraction wires



**Fig. 1.** Schematic cross section of the simulated HJT solar cell without front metallization.



**Fig. 2.** Schematic top view of measurement setup with 12 current contact wires/bars (orange) including two sensing contacts (red) for precise voltage measurements. The magnification shows the unit cell used for the simulations.



**Fig. 3.**  $I$ - $V$  (compact line) and  $P$ - $V$  (dashed line) curves around the maximum power point of HJT solar cells with sheet resistances of (a)  $1 \Omega/\text{sq}$  and (b)  $200 \Omega/\text{sq}$  for different positions of the voltage sense contact  $d_{sp}$  using a contacting unit consisting of 12 current wires. The respective MPPs are depicted as crosses.

with neglected contact resistance. The fingers on the rear side of the cell are contacted by a full area contact. The cells have a wafer size of  $156.75 \times 156.75 \text{ mm}^2$ .

Figure 2 shows the schematic top view of the solar cell, here connected by 12 wires for  $I$ - $V$  measurements, including the voltage sense contacts positioned in proximity to one of the wires/bars. For the FEM simulations the cell is divided into an unit cell which is periodic in both x- and y-direction (see magnified part). Pads (dark yellow) are positioned on two sides of the unit cell for contacting. They are chosen to be transparent to prevent an influence on  $I_{sc}$  and  $V_{oc}$ .

Bothe et al. showed the voltage distribution under maximum power point conditions only. This is not sufficient when going to higher lateral resistivities. In Figure 3 the current-voltage and power-voltage curves for sheet resistances of  $1 \Omega/\text{sq}$  and  $200 \Omega/\text{sq}$  are plotted for a contacting unit using 12 wires but different relative positions of the voltage sense contact  $d_{sp}$  of 0 (at the current contact), 0.2 and 0.5. Since the open circuit voltage and short circuit voltage are set to be similar for all cells, the curves are only shown around the maximum power point. The curves and thus the maximum power points differ significantly from each other for high sheet

resistances when placing the position of the sense contact at different positions. Therefore, we extract the  $V_{MPP}$  and  $J_{MPP}$  to calculate the fill factor for each position of the voltage sense contact  $d_{sp}$ . The resulting fill factor distribution over the position of the voltage sense contact is then compared to the equipotential voltage distribution resulting from a full contacting of the cell. The latter is achieved by adding a transparent pad over the complete unit cell. Placing the voltage sense contact at the intersect between the distributions for different sheet resistances and number of wires and the distribution of a fully contacted cell allows to measure the fill factor of these cells neglecting the lateral resistance.

## 2.2 Measurements

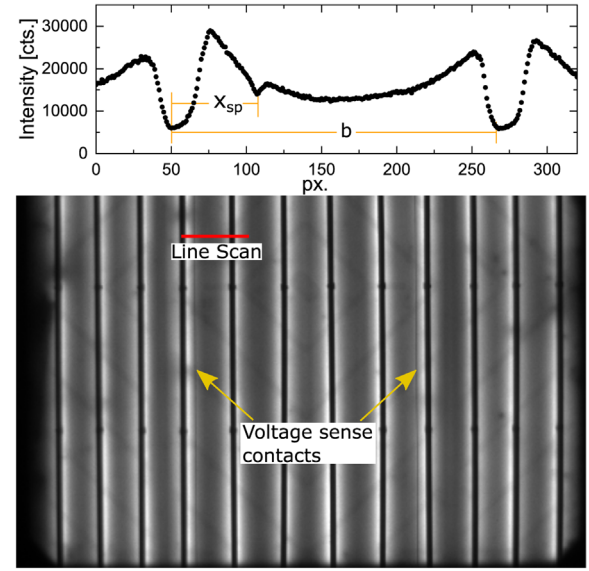
To verify our simulations, we measure three HJT cells with a TCO made of indium tin oxide (ITO) with two measurement systems with different contacting frames. Varying the oxygen content in the ITO results in different sheet resistances. The first system (abbr. as LOANA) manufactured by pv-tools consists of 12 elastic contacting bars with two voltage sense contacts. The second system from Pasan SA uses 30 wires over a bended surface to contact a solar cell with 5 additional voltage sense contacts (abbr. as PASAN). For both systems the reproducibility of the measured  $FF$  is better than  $0.1\%_{abs}$  when contacting the cell several times. To verify the comparability of the two systems we also characterized fully metallized HJT solar cells with both measurement systems. We found an agreement of the measured open circuit voltage, short circuit current, fill factor and efficiency within  $1\%_{abs}$  of all values.

The positions of the voltage sense contacts are determined from electroluminescence (EL) pictures by using a linescan over the 2 bars with a sense contact in between (see Fig. 4). By measuring the distance between two current bars  $b$  and the distance between one current bar and the voltage sense contact  $x_{sp}$  we calculate the relative position of the voltage sense contact between the two current bars. The precision of this method depends on the resolution of the EL image which is 16 px/cm for the LOANA system and 6.4 px/cm for the PASAN measurement system. The average relative position of each sense contact of the LOANA is  $0.2 \pm 0.02$  between the current extraction wires/bars and  $0.35 \pm 0.1$  for the PASAN Spotlight system. Both uncertainties are dominated by the resolution of the EL images.

## 3 Results

### 3.1 Simulations

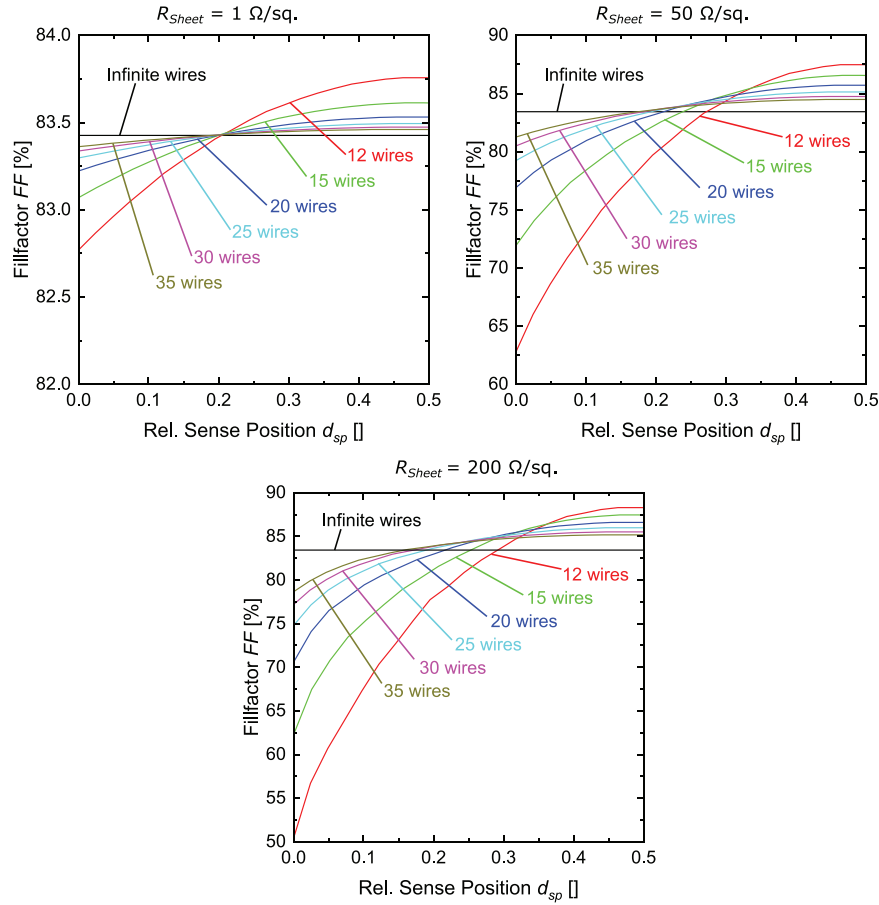
We simulate the fill factor distribution of solar cells with TCO sheet resistances ( $R_{Sheet}$ ) between  $1 \Omega/sq$  to  $200 \Omega/sq$  and for a different number of wires between 12 and 35 distributed equidistantly over the cell area. While  $1 \Omega/sq$  is an optimistic assumption for a TCO, it has been shown to be achievable with low losses in transparency [15].



**Fig. 4.** EL picture of a HJT solar cell without front metallization contact with 12 bars and 2 voltage sense contacts. A line scan is performed to determine the distance  $b$  between two current contacts and  $x_{sp}$  of the voltage sense to a current wire.

The resulting fill factor distributions are plotted over the relative position of the voltage sense contact  $d_{sp}$  between two adjacent current wires/bars in Figure 5, exemplary for sheet resistances of the TCO of  $1 \Omega/sq$ ,  $50 \Omega/sq$  and  $100 \Omega/sq$ . The approximately parabolic distributions are symmetric around the centre of the current wires. Therefore, the fill factor is only plotted in the range from  $d_{sp} = 0$  to  $0.5$ . Additionally, the fill factor of the fully contacted cell is plotted. For a small sheet resistance of  $1 \Omega/sq$  the distributions of all number of wires intersect the fill factor achieved by a full contacting of the metal grid. A *grn* measurement would be still possible when placing the sense contact at  $d_{sp} = 0.2$  for a HJT solar cell without metallization and a very low sheet resistance. This is consistent with the results of Bothe et al.

This dependency does not hold with rising sheet resistances. The fill factor distributions shown in Figures 5b and 5c don't cross the black line representing the fully contacted cell at a specific position. For 12 and 15 wires the sense position for a grid resistance neglecting measurement shifts closer to the centre between two current wires resulting in an underestimation of the fill factor when sensing the voltage at  $d_{sp} = 0.2$ . Measuring a cell with a TCO sheet resistance of  $200 \Omega/sq$  with 12 wires and a sense contact placed at  $d_{sp} = 0.2$  leads to a  $FF$  which is  $5.2\%_{abs}$  lower than the  $FF$  of a fully contacted cell. Using 20 and more wires results in an opposing trend and the fill factor will be overestimated for voltage sense position at  $d_{sp} = 0.2$ . Contacting a  $200 \Omega/sq$  cell with 35 wires and sensing the voltage at  $d_{sp}$  results in an overestimation of  $0.6\%_{abs}$ .



**Fig. 5.** Fill factor between two current wires at *MPP* conditions for a HJT solar cell with  $R_{\text{Sheet}} = 1 \, \Omega/\text{sq}$ ,  $50 \, \Omega/\text{sq}$  and  $200 \, \Omega/\text{sq}$ .

Similar simulations for the other TCO sheet resistances are used to identify the optimal sense contact positions summarized in Figure 6a. For small sheet resistances, they are at  $d_{sp} = 0.2$ , nearly independently from number of wires. Going to higher sheet resistances the position of the voltage sense for a grid resistance neglecting measurement shifts. Using a low amount of wires results in shift of the sense contact towards the middle of the current wires converging at 0.28 for 12 wires and 0.25 for 15 wires for sheet resistance up to  $200 \, \Omega/\text{sq}$ . The large voltage drop between two adjacent current wires results in different operating points of the cell depending on the distance to the current wires which are different from the maximum power point. Not only  $V_{\text{MPP}}$  changes but also  $J_{\text{MPP}}$  is considerably different (compare Fig. 3).

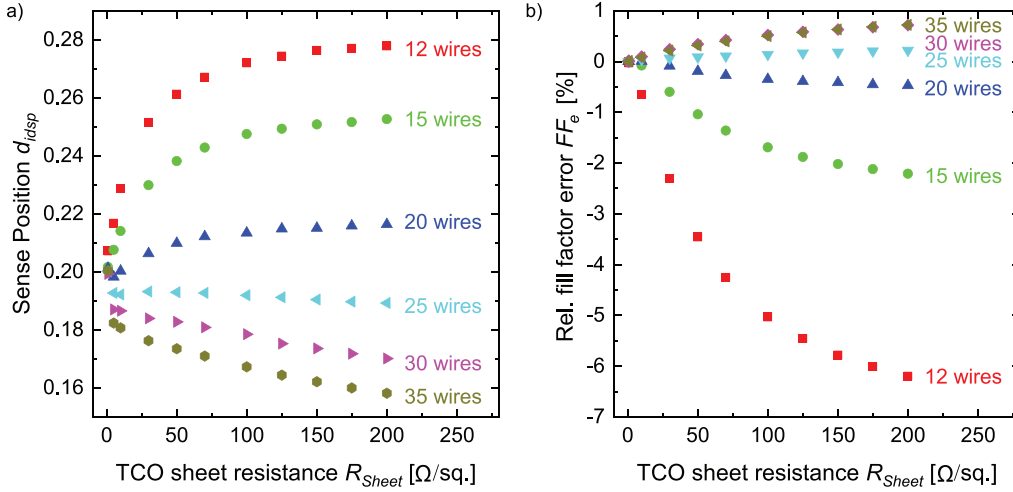
On the other hand, using more wires results in a shift of the voltage sense position for the grid resistance neglecting measurement closer to one of the current wires. The lower voltage gradient between two adjacent wires allows similar operating points over the whole cell and the fill factor distributions follow the voltage distribution showing the same behaviour. There seems to be an ideal number of wires of 23 resulting in the same position of the voltage sense contact for a grid resistance free measurement independent of the TCO sheet resistance. For the given wafer size of

$156.75 \times 156.75 \, \text{mm}^2$  23 wires correspond to a distance between two current wires of 7 mm. While this might be true for the specific cell parameters we simulated here we can not confirm this for solar cells with different properties at the moment.

Additionally, we investigate the error in fill factor measurements when placing the sense contact placed at a fixed position of 0.2, i.e. the ideal position for metallized cells and cells with small resistivity. Using only 12 wires the error is up to  $6.2\%_{\text{rel}}$  ( $5.2\%_{\text{abs}}$ ) for cells with a sheet resistivity of  $200 \, \Omega/\text{sq}$  as shown in Figure 6b. For 30 or 35 wires the error is considerably smaller with an overestimation of the *FF* up to  $0.7\%_{\text{rel}}$  ( $0.6\%_{\text{abs}}$ ) allowing for a much improved accuracy of the *I-V* measurement. The measurements are most robust regarding the TCO sheet resistance when using 25 wires with an error in the fill factor measurement of  $0.2\%_{\text{rel}}$  ( $0.17\%_{\text{abs}}$ ) due to non ideal placing of the voltage sense contact.

The fill factor distributions in Figure 5 show rising gradients for fewer wires (and thus greater distance between the wires). Therefore, we analyse the simulations regarding the uncertainty of the positioning of the voltage sense contact and the resulting uncertainty in *FF* measurements (see Fig. 7). Assuming a placement accuracy for the voltage sense contact of 0.25, which is the case for





**Fig. 6.** (a) Simulated relative position of the voltage sense contact for a *grn* *FF* measurement depending on the TCO sheet resistances. (b) Relative error  $FF_e$  of the fill factor measurement when placing the sense contact at  $d_{sp} = 0.2$  depending on number of wires used for contacting and sheet resistance of TCO.

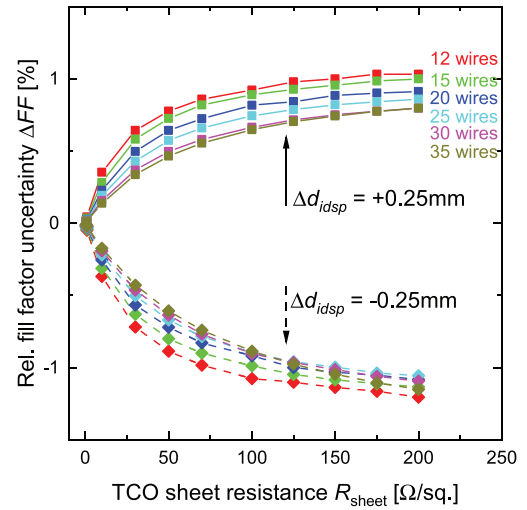
the LOANA system, the *FF* can be overestimated up to 1.0%<sub>rel</sub> (0.8%<sub>abs</sub>) for contacting geometries with a low amount of contacting bars/wires. On the other hand, if the sense is too close to the current extraction wire, the *FF* is underestimated up to 1.2%<sub>rel</sub> (1.0%<sub>abs</sub>). The asymmetry of the over- and underestimation of the *FF* is caused by the increasing gradient of the fill factor distributions with decreasing distance of the sense contact to the current wires. A contacting unit with 35 wires has an ideal sense position shifted closer to smaller relative sense positions with rising sheet resistances resulting in an higher uncertainty of the *FF* measurement compared to a contacting with less wires.

For rising  $R_{Sheet}$  of the TCO contacting systems with a larger number of wires are more robust due to the smaller gradient of the fill factor distribution. Nevertheless, the measurements are very sensitive to the position of the voltage sense contact. To measure the *FF* of a solar cell having TCO sheet resistances up to 200 Ω/sq with an uncertainty smaller than 1%<sub>rel</sub> using a contacting unit consisting of 12 wires, the sense contact has to be positioned with an accuracy of 0.21 mm. or better.

### 3.2 Measurements

The *FF*-measurements of three solar cells without a metallized front side and different TCO sheet resistances of 72 Ω/sq, 123 Ω/sq and 175 Ω/sq are compared to validate the simulations. The series resistance free pseudo fill factor extracted from the  $J_{SC}$ - $V_{OC}$  curve of these cells is nearly the same with 85.2%, 85.6% and 85.3%, respectively.

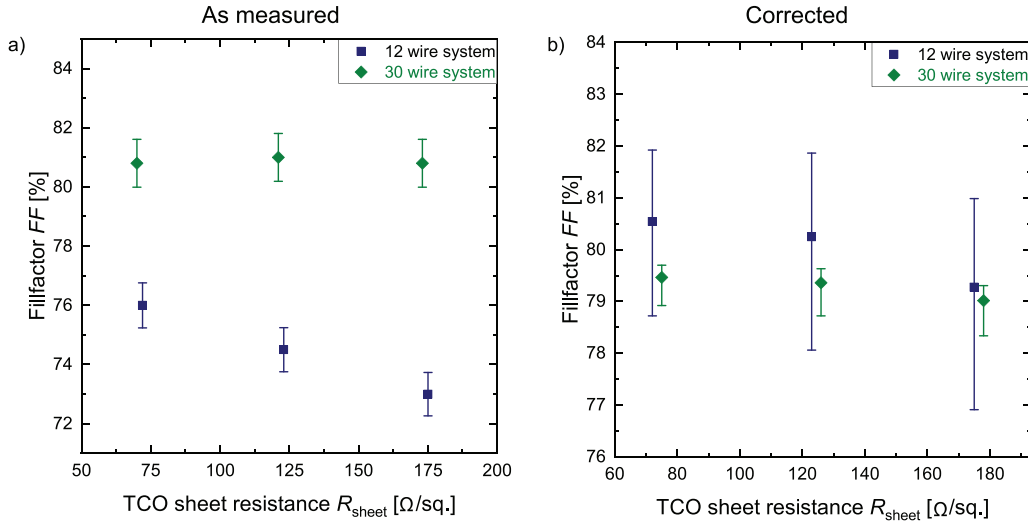
For the three different cells, the voltage sense contact would be ideally positioned at 0.265 (0.181), 0.273 (0.175) and 0.277 (0.171) for the LOANA (PASAN) system, respectively (see Fig. 6a). The non-ideal placement of the voltage sense contacts of 0.2 for the LOANA and 0.35 of the PASAN system (see Sect. 2.2) results in larger differences



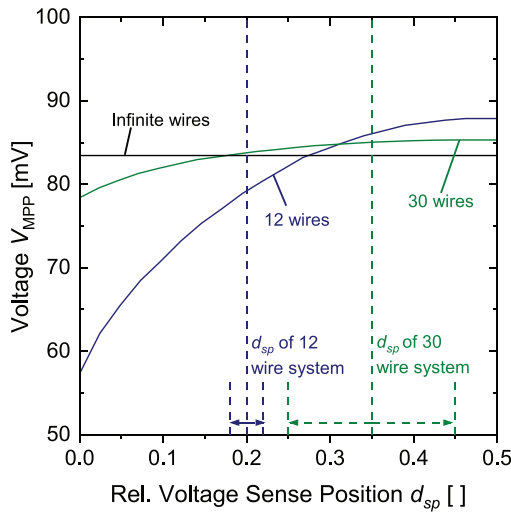
**Fig. 7.** Rel. uncertainty in *FF* – measurement due to a misplacement of  $-0.25$  (diamonds, dashed line) and  $+0.25$  (squares, compact line) of the voltage sense contact depending on  $R_{Sheet}$  of the TCO for different wire/bar distances.

between the measured *FF* of the two systems the higher the sheet resistance of the TCO. For  $R_{Sheet} = 175$  Ω/sq the discrepancy in *FF* is up to 7.5%<sub>abs</sub> as shown in Figure 8a.

By using our simulations, we can estimate the influence of non-ideal positioning of the voltage sense contact. In Figure 9 the voltage distribution between adjacent current contacts of the cell with a sheet resistance of 123 Ω/sq is shown for the contacting units of the two measurement systems and compared to the voltage of a fully contacted cell at the sense respective positions  $d_{sp}$ . We extract the overestimation of the fill factor measurement and add the difference to the measured fill factors resulting in a corrected *FF* were the non-ideal position of the voltage



**Fig. 8.** Measured  $FF$  of 3 cells with different TCO sheet resistance for two different setups (blue: 12 wires, rel. sense position = 0.2; green: 30 wires, rel. sense position = 0.35). In (a) the directly measured values are shown. In (b) the  $FF$  of the same measurement setup and cells but with corrected values for the misplaced voltage sense contact is plotted.



**Fig. 9.** Simulated fill factor distribution of a HJT cell without front metallization and  $R_{\text{sheet}} = 123/\text{sq}$  compared against fill factor of a fully contacted cell. The uncertainty of the voltage sense position is illustrated at the bottom.

sense contact is compensated. The correction values  $\Delta_{FF}$  (LOANA) and  $\Delta_{FF}$  (PASAN) for the two contacting units are summarized in Table 1.

By correcting the measured  $FF$  with these values, we are able to reduce the maximum difference between the two measurement setups to below  $1.5\%_{\text{abs}}$ . The uncertainty range in Figure 8b indicate the additional uncertainty due to the positioning precision of the voltage sense contact determined from EL pictures (see Sect. 2.2). In Figure 9 the uncertainty of the voltage sense position  $d_{\text{sp}}$  is shown. Due to the higher gradient of the voltage distribution for the contacting unit with 12 wires the uncertainty is higher for this system. The proposed post-processing of the measurements allows reconstructing of a grid resistance neglecting

**Table 1.** Correction values for the  $FF$  to compensate for the non-ideal position of the voltage sense contact for the two used contacting units.

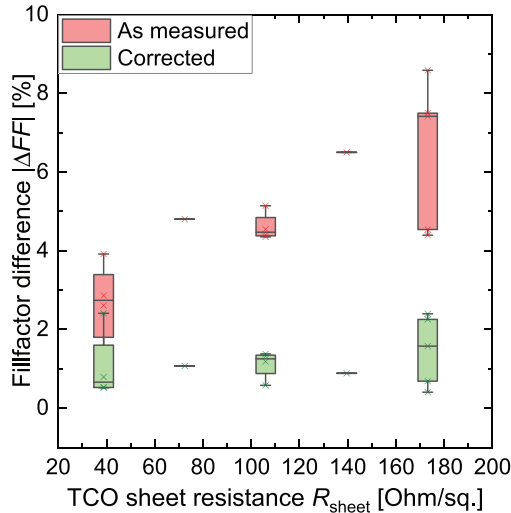
| $R_{\text{sheet}}$ [ $\Omega/\text{sq.}$ ] | $\Delta_{FF}$ (LOANA) | $\Delta_{FF}$ (PASAN) |
|--------------------------------------------|-----------------------|-----------------------|
| 72                                         | +4.5                  | -1.3                  |
| 123                                        | +5.7                  | -1.6                  |
| 175                                        | +6.3                  | -1.8                  |

measurement of HJT solar cells without front metallization with two different measurement systems.

We measured additional solar cells with sheet resistances between  $40 \Omega/\text{sq}$  and  $175 \Omega/\text{sq}$  with both systems. The differences of the directly measured fill factors between the two systems are shown in Figure 10. They are compared against the  $FF$  difference after correcting the values according to the simulations as described before. The differences are increasing for rising sheet resistances from  $2.7\%_{\text{abs}}$  on average for  $R_{\text{sheet}} = 40/\text{sq}$  to  $7.5\%_{\text{abs}}$  on average for  $R_{\text{sheet}} = 175/\text{sq}$ . The underestimation and overestimation of the 12 wire and 30 wire system, respectively, is compensated. This reduces the difference of the fill factor measurements to below  $1.5\%_{\text{abs}}$  on average and are in good agreement with our simulations.

## 4 Discussion

Going towards solar cells without front metallization poses new challenges on the accurate measurement setups of solar cells. The grid-resistance neglecting contacting concept for metallization-free HJT cells requires precise positioning of the voltage sense contact. Also, when measuring cells with different sheet resistances of the TCO the voltage sense contact has to be repositioned. On the other hand, it is plausible to place the voltage sense at a



**Fig. 10.** Absolute difference of the  $FF$  measured by the 12 and 30 wire system compared to absolute difference after correction according to simulations.

fixed position and to compensate the  $FF$  and efficiency measurements afterwards with simulation comparable to those presented in this paper. This requires a precise knowledge of the cell for an accurate representation in the simulation. For unknown solar cells the deviation of the fill factor from the  $grn$  value due to the lateral resistance and the position of the voltage sense contact can be estimated by determining the sheet resistance with a measurement of the series resistance between two current wires.

Nevertheless, as shown in Figure 5, the voltage at the current extraction rods, i.e. a relative position of the voltage sense  $d_{sp}=0$ , is considerably lower than the equipotential voltage distribution. In a PV module only the voltage at the wire can actually be utilized. Therefore, for HJT solar cells without metallization a *grid-resistance including* contacting scheme seems to be more suitable. Placing the voltage sense contact very closely to the current extraction wire gives a more realistic representation of the cell performance in the module.

## 5 Conclusion/summary

We perform FDM simulations to test the approximation of Bothe et al. on the contacting of busbarless solar cells during  $I$ - $V$  measurements for HJT solar cells without front metallization. The fill factor distribution between two contact wires/ bars is simulated for various sheet resistances of the front TCO. We can confirm the results of Bothe et al. with our simulations for small sheet resistances. Going towards higher sheet resistances of metallization free HJT solar cells the optimal relative position of the voltage sense contact becomes dependent of the sheet resistance of the TCO and the number of wires used for contacting. Simulating different wire distances, we observe high sensitivity of fill factor measurements to the positioning of

the voltage sense contact. Misplacing the voltage sense contact by  $\pm 0.25$  leads to an uncertainty in  $FF$ -measurement of up to  $1.2\%_{rel}$ , depending on the sheet resistance of the TCO and wire geometry. Estimating the resulting errors in  $FF$ -measurements due to the uncertainty in positioning the sense contact gives a precision requirement for  $\Delta FF < 1\%_{rel}$  of the voltage sense contact to 0.21 mm for 12 contacting wires and TCO sheet resistances up to  $200 \Omega/sq$ .

We measure HJT cells without front metallization with varying sheet resistances with two different measurement systems using 12 (2) bars and 30 (5) wires for current extraction (voltage sensing). By correcting for the voltage sense contact position using the simulation results, we can reduce the difference in  $FF$ -measurements between the two setups from 7.5% to below 1.5%, with both values within their respective confidence range.

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## Author contribution statement

Malte Brinkmann, main author: Conduction of simulations and measurements, writing of paper. Felix Haase: Preparation of simulation study and measurements, proofreading. Karsten Bothe: Characterization expert, guiding the simulations and measurements, proof-reading. Karsten Bittkau: simulation expert, support and discussion of simulation results, proof-reading. Andreas Lambertz, Weiyuan Duan, Kaining Ding: HJT solar cell experts, preparation of cells for measurements, discussion. Hans-Peter Sperlich, Andreas Waltinger: Project coordinator, preparation of cells for measurements, discussion. Henning Schulte-Huxel: Discussion, proof reading.

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