Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 124 (2017) 84–90

Energy Procedia

www.elsevier.com/locate/procedia

7th International Conference on Silicon Photovoltaics, SiliconPV 2017

Impact of contacting geometries on measured fill factors

Christian N. Kruse[a,]*, Martin Wolf [a], Carsten Schinke[a,b], David Hinken[a], Rolf Brendel[a,b], Karsten Bothe[a]

[a] Institute for Solar Energy Research Hamelin (ISFH), Am Ohrberg 1, Emmerthal 31860, Germany
[b] Institute for Solid State Physics, Leibniz Universität Hannover, Appelstraße 2, 30167 Hannover, Germany

Abstract

The fill factor determined from a measured current-voltage characteristic of a bare solar cell depends on the number and positions of the electrical contacting probes. Nine different geometries for contacting the front side busbars are used to measure the current-voltage (I-V) characteristics of a 5 busbar industrial-type passivated emitter and rear totally diffused (PERT) solar cell under standard testing conditions. The fill factors of the measured I-V characteristics vary from 78.5 $\%_{abs}$ to 80.6 $\%_{abs}$. We further measure the contacting resistance of 3 different contacting probes to estimate the sensitivity of measurements with different contacting geometries on random resistance variations. The contacting resistance is 60 mΩ for nine-point probes and 80 mΩ for four- and single-point probes. We determine the magnitude of contacting resistance variations from measurements at different probe positions to be ±30 mΩ. Using this variation, we perform numerical simulations and find a larger sensitivity on random resistance variations for tandem- (pairs of current- and sense probes) compared to triplet (one sense- between two current probes) configurations. The corresponding fill factor deviation is approximately 0.1$\%_{abs}$ for tandem configurations when the contacting resistances of up to two current probes are altered. The sensitivity for triplet configurations is negligible.

Peer review by the scientific conference committee of SiliconPV 2017 under responsibility of PSE AG.

Keywords: Characterization of PV; Current-voltage characteristics; Fill Factor

---

* Corresponding author. Tel.: +49-5151-999-632; fax: +49-5151-999-400.
E-mail address: c.kruse@isfh.de

1876-6102 © 2017 The Authors. Published by Elsevier Ltd.
Peer review by the scientific conference committee of SiliconPV 2017 under responsibility of PSE AG.
10.1016/j.egypro.2017.09.329

1. Introduction

The measurement of the current-voltage (I-V) characteristic is essential for classifying solar cells. A variety of measurement setups is commercially available for this purpose. Comparing measurement results obtained with different setups is not trivial, as the setups may differ in terms of illumination conditions, temperature control and the electrical contacting of the cell. This paper focuses on the impact of different geometries for contacting the front side of a solar cell on the fill factor (FF) of measured I-V characteristics. The front side of a solar cell is commonly contacted in a four wire configuration with contacting probes mounted in a narrow bar to minimize shading. The number and positioning of the contacting probes along the bar can be very different between individual measurement setups. One possibility to contact a solar cell for an I-V measurement is to place the contacting probes to reflect the module integration of the solar cell which is, for example, suggested in [1], [2]. However, the module integration of cells can differ and measurement results obtained with this contacting approach cannot be easily compared for different measurement setups. Another approach is to measure the cell such that the results are comparable across different setups. To achieve this comparability the contacting probes can be placed such that the busbar (BB) resistance is neglected [3]–[5]. In this work we measure the I-V characteristics of a 5 BB solar cell using 9 different contacting geometries in order to estimate the implied systematic deviations between measurements with different contacting geometries. We further measure the contacting resistance of different test probes and analyze the differences between tandem and triplet configurations in terms of their sensitivity on random variations of the contacting resistance using numerical device simulations.

2. Contacting geometries

2.1. Variable contacting bar

In order to measure I-V curves of the same solar cell with a variety of different contacting geometries we use a freely configurable contacting bar manufactured by pv-tools [6] which is shown in figure 1. This contacting bar features two low-resistivity conducting paths which are insulated from each other. The first serves as current conducting path and the second for voltage sensing. The contacting probes can be mounted in a total of 31 slots and then connected to either of the conducting paths using a jumper cable. The distance between the slots is 5 mm. The connection to the conducting path for voltage sensing is realized over a 500 Ω resistor to minimize current flow over the conduction path. The low resistivity of the current conduction path ensures that all current contacting probes are at the same potential.

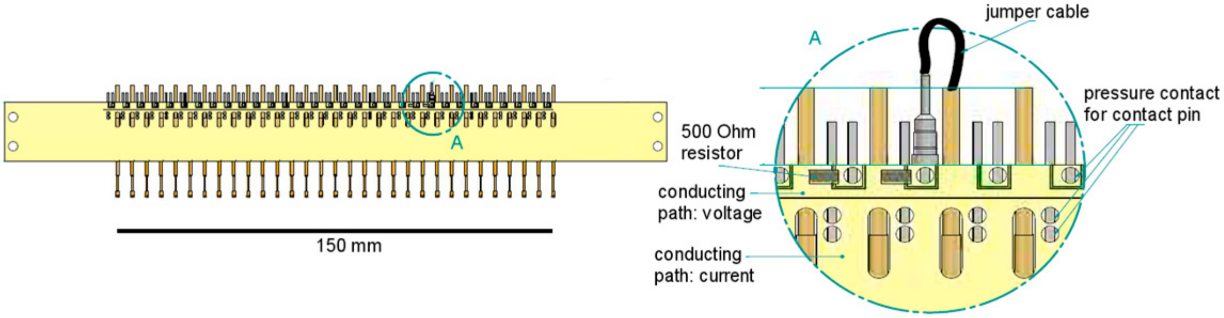

Fig. 1. Variable contacting bar with a total of 31 removable test probes. Each of these test probes can be used as a sense or a current probe by connecting the jumper cable to the respective conducting path.

2.2. Measuring the busbar resistance

The deviations between measurements with different contacting geometries arise from potential variations along the BBs of the solar cell. The main impact on this potential variation rises from a nonzero BB resistance and the resulting voltage drop caused by the current flow through the BB. Consequently, the difference between measurements with different contacting geometries depends on the BB resistance and the current collected by each BB. To estimate the range of the BB resistivity for modern 5 BB industrial solar cells we measure the BB resistance of different front side metallizations. For the measurement we cut a stripe of approximately 10 mm width containing the entire BB from the cell, to minimize the impact of parallel resistances. The resistivity of the BB on the stripe is then determined using a four-wire setup. We measure a variety of 5 BB solar cells manufactured at ISFH with different printing techniques and silver pastes and obtain values between 6 and 34 Ω/m for the BB resistivity.

2.3. Impact of different contacting geometries on the measured fill factor

We use a 5 BB passivated emitter and rear totally diffused (PERT) solar cell for our analysis. This cell features a front metallization design with 0.5 mm wide, screen printed BBs with a resistivity of 34 Ω/m. The high but still realistic BB resistivity enables us to estimate the maximum expectable difference between measurements with different contacting geometries. The front metallization was screen-printed in two separate steps, one for the contact fingers and one for the busbars. Further details of the solar cell can be found in reference [7]. For this cell we measure the I-V characteristics with the contacting geometries displayed in figure 2(a). The contacting geometries 1 through 8 are designed for the variable contacting bar introduced in the previous section. Contacting geometry 9 is the contacting geometry currently used by the ISO 17025 accredited Solar Cell Calibration and Test Center (CalTeC) at ISFH. The measurement results are shown in Fig. 2(b) (green bars) along with an independent reference measurement of the FF at ISE CalLab (red solid line). The measured fill factors show systematic deviations of up to 2 %$_{abs}$, depending on the contacting geometry, which corresponds to a difference in measured energy conversion efficiencies of up to 0.5 %$_{abs}$. The FF deviations related to the different contacting geometries are considerably larger than the uncertainty of the reference measurement (red dashed lines), indicating the necessity for a careful selection of the contacting scheme for precise I-V measurements. Please note that the black error bars do not indicated the full measurement uncertainty but only the statistical uncertainty of 10 reproducibility measurements each after re-contacting the cell. The full FF uncertainty of our setup is about 0.6%$_{abs}$ and thus comparable to the reference measurement.

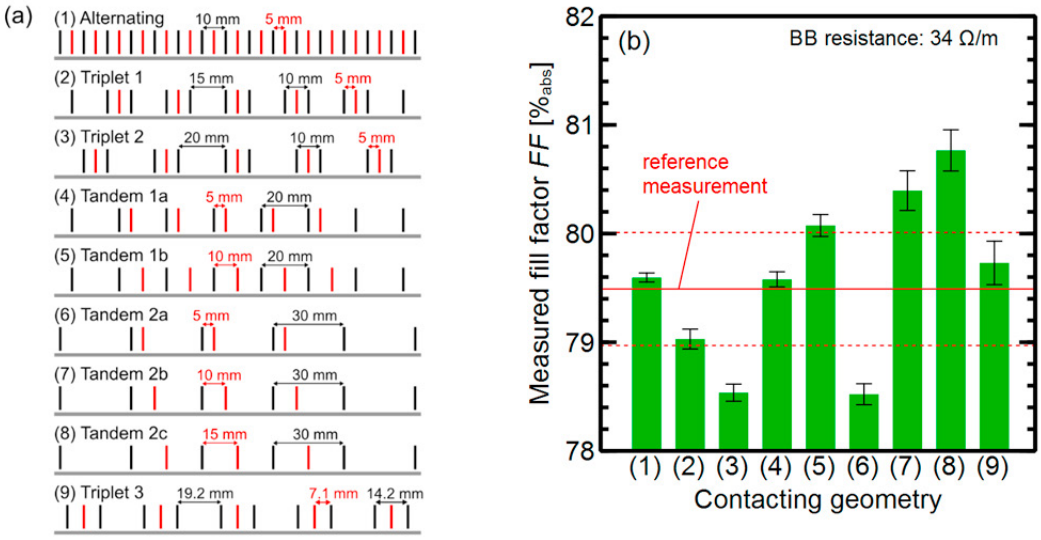

Fig. 2. (a) Different schemes of current (black) and sense (red) contacting probes (b) Fill factors measured with the displayed contacting geometries and comparison to an independent reference measurement at ISE CalLab. The dashed red lines show the uncertainty of the reference measurement.

The contacting geometry (9) was designed to ensure a good comparability between different measurement setups by probing the average busbar potential and thus minimizing the impact of the busbar resistance [3]. Probing at a higher potential (further away from the current probe) shifts the entire I-V curve towards higher voltages and thus leads to an overestimation of the FF compared to probing the average BB potential (contacting geometry 5, 7 and 8). Similarly, the FF is underestimated when probing at lower voltages (contacting geometry 2, 3 and 6). This clearly shows the necessity of a careful design of contacting geometries depending on the purpose of the measurement. Since any over- or underestimation depends on the BB resistance and thus differs for each individual cell, we suggest probing the average BB potential to ensure a comparability between different measurement setups.

3. Inhomogeneous contacting resistance

The contacting probes used to contact the front side of a solar cell are spring loaded such that the contact surface is pressed against the BB. The contacting resistance is determined by the contact pressure and the surface properties of the probe and the BB [8]. In contrast to soldered contacts, this type of contacting leads to larger variations of the contacting resistances in an I-V measurement. In this section we measure the contacting resistance of different test probe designs and analyze the impact of random resistance variations on the measured fill factor for different contacting geometries.

3.1. Experimental determination of contacting resistances

We determine the contacting resistance by measuring the resistance between two contacting probes at different distances using four-wire contacting. This yields the sum of the BB resistance and both contacting resistances. We then linearly extrapolate the measurement results for zero distance between the test probes to determine the combined contacting resistance of both probes. The contacting resistance of one test probe is half the resistance determined from the extrapolation. It should be noted that the contacting resistance depends not only on the test probes but also on the BB, especially the BB width.

We measure the contacting resistances for three types of test probes: single-point, four-point crown-type and nine-point crown-type probes (see Fig. 3). For single- and four-point probes we determine contacting resistances of 80 mΩ, for nine-point probes we measure a contacting resistance of 60 mΩ. It should be noted that for four-point probes some probes did not contact the busbar at all, although the contact surface was placed across the busbar. This rises from the small busbar width of only 500 µm which is smaller than the distance between the four contact points of the probe. This allows a situation where two contact points of the probe are placed on each side of the busbar without touching it. This issue will become increasingly important since busbar widths tend to decrease continuously. Data points for which no contact was observed where neglected in the evaluation but this possibility should be kept in mind for the choice of contacting probes for an I-V measurement. As nine-point probes are the most reliable contacting probes for narrow busbars and apply the least local pressure to the solar cell, we recommend their use for present solar cells featuring busbar widths on the order of 500 µm.

The measurements were carried out between one probe at the same BB position for all data points and a second probe at one BB location for each distance. Consequently, we take the deviations of the data points from the linear fit as an estimate for the magnitude of uncontrolled resistance variations. We find resistance variations of ±30 mΩ for nine-point probes.

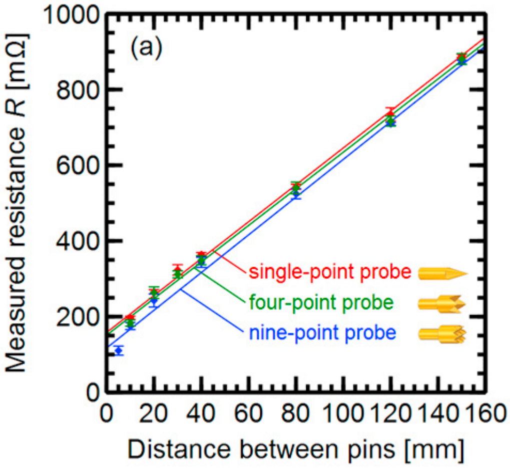

Fig. 3. Measured contacting resistances for different test probes (ingun GKS-101). The images of the test probes were reprinted from the ingun test probe catalogue 2010/2011 [9] . The magnitude of resistance variations is estimated by the maximum deviation of the data points from the linear fit and determined to 30 mΩ for nine-point probes.

3.2. Impact of varying contacting resistances on the measured fill factor

We analyze the impact of contacting resistance variations on measurements with different contacting geometries. The contacting geometries in figure 2(a) can be divided into two groups: tandem geometries consisting of current and sense probe pairs and triplet geometries consisting of groups of one sense between two current probes. We choose the geometries Tandem 1a (tandem group) and Triplet 3 (triplet group) as both geometries feature a comparable number of contacting probes and show similar fill factors in the measurement in figure 2(b).

To estimate the impact of contacting resistance variations on the fill factor, we perform numerical calculations by employing the solar cell device simulator Griddler [10]. For a reference simulation we use a contacting resistance of 60 mΩ for the test probes. To estimate the maximum expectable difference, we then alter the contacting resistance of individual current probes (see figure 4(a)) to 30 mΩ or 90 mΩ, corresponding to the determined contacting resistance variation. It should be noted that the results do not depend on the exact location of the resistance variation as long as it is adjacent to a sense probe. The results of the simulation are shown in figure 4(b). Although both contacting geometries have 5 voltage probes and a similar number of current probes (8 and 10), we see that for the triplet configuration the fill factor is almost independent of the contacting resistance variation with a deviation on the order of 0.01%$_{\mathrm{abs}}$, while for the tandem configuration the FF deviation can be larger than 0.1 %$_{\mathrm{abs}}$.

Every deviation of the contacting resistance of an individual current probe causes a change in the busbar potential at the location of the contacting probe. Furthermore, the total current extracted from the solar cell changes. For a decreased contacting resistance of a current probe the current increases while the busbar potential at the probe position decreases and vice versa. An increased current leads to an increased fill factor while the decreased potential corresponds to a decrease of the fill factor. Depending on which of these effects is dominating, the fill factor can in- or decrease with a contacting resistance variation of an individual current probe. The change of the extracted current depends on the total number of current probes and is, consequently, slightly smaller in the triplet configuration as it features 10 current probes compared to 8 current probes of the tandem configuration. However, the results in figure 4(b) show that the FF deviation is positive for a reduced contacting resistance and, thus, the change of the extracted current is the dominating contribution for the triplet configuration. For the tandem configuration the potential variation is the dominating contribution. Consequently, the difference of both contacting geometries rises from their different sensitivity on potential variations at the current probe positions. The sensitivity on potential variations depends on the total number of sense probes, which is the same for both analyzed contacting geometries. However, in the tandem configuration each potential variation at a current probe position affects the voltage measured by two sense probes. Furthermore, one sense probe is located close to the current probe (4.2 mm in the case of Tandem 1a) and a potential variation at the current probe has a large impact on the potential at the adjacent sense probe position. In contrast to that, the sense probes in the triplet configuration are placed in the center between to current probes. Thus, the potential variation at the sense probe position is smaller for this configuration. Furthermore, a variation of the contacting resistance of a current probe only affects one sense probe. Consequently, the impact of potential variations due to contacting resistance variations is considerably smaller in triplet than in tandem configurations.

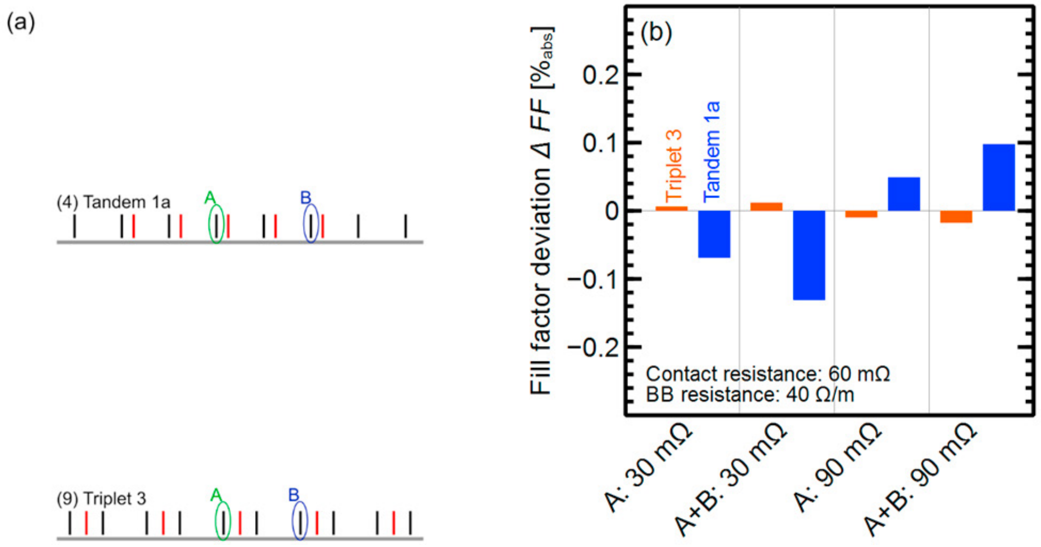

Fig. 4. (a) Contacting geometries used for the simulation and probe positions for which the contacting resistance was varied. (b) Numerical simulation for varying contacting resistances. The probes not specified on the x-axis feature a contacting resistance of 60 mΩ.

4. Summary

We experimentally compared different contacting geometries and measured fill factors ranging from 78.5 $\%_{abs}$ to 80.6 $\%_{abs}$ for the same industrial PERT solar cell. Thus, the contacting geometry has a large impact on the measurement result and should be chosen carefully. We also measured the contacting resistance of three different contacting probe designs and studied the impact of contacting resistance variations on the measured fill factor by means of solar cell simulations. We found that triplet configurations are less sensitive to inhomogeneous contacting resistances than tandem configurations. The latter showed fill factor deviations on the order of 0.1$\%_{abs}$ for contacting resistance variations of ±30 mΩ at individual current probes, compared to 0.01$\%_{abs}$ for triplet configurations. Our recommended contacting geometry for comparable measurements is a triplet configuration with sense probes positioned such that the average busbar potential is measured. This recommendation is in agreement with previous studies [5], [3]. Following this recommendation will improve the consistency of FF results from different setups.

Acknowledgements

This work has been part of the European Metrology Research Programme (EMRP). The EMRP is jointly founded by the EMRP participating countries within EURAMET and the European Union.

References

[1] R. A. Sinton, “Characterization issues for bifacial solar cells,” presented at the *bifi PV Workshop Konstanz*, 2012.

[2] K. A. Emery, “How [NOT] to measure a solar cell to get the highest efficiency,” presented at the *43rd IEEE Photovoltaic Specialists Conference*, 2016.

[3] C. N. Kruse, M. Wolf, C. Schinke, D. Hinken, R. Brendel, and K. Bothe, “Impact of Contacting Geometries When Measuring Fill Factors of Solar Cell Current–Voltage Characteristics,” *IEEE J. Photovoltaics*, 2017, [Online]. Available: http://dx.doi.org/10.1109/JPHOTOV.2017.2677084.

[4] I. Geisemeyer, C. Kallies, J. Hohl-Ebinger, and W. Warta, “Contacting bare silicon solar cells with advanced cell metallisation,” *29th European PV Solar Energy Conference and Exhibition*, 2014, pp. 1202–1207.

[5] J. Hohl-Ebinger, D. Grote, B. Hund, A. Mette, and W. Warta, “Contacting bare solar cells for STC measurements,” in *23rd European Photovoltaic Solar Energy Conference and Exhibition*, 2008, pp. 2012–2016.

[6] pv-tools GmbH, D-88289 Waldburg, Germany. [Online]. Available: www.pv-tools.de.

[7] B. Lim, T. Brendemühl, T. Dullweber, and R. Brendel, “Loss analysis of n-type passivated emitter rear totally diffused back-junction silicon solar cells with efficiencies up to 21.2%,” *IEEE J. Photovoltaics*, vol. 6, no. 2, pp. 447–453, 2016.

[8] B. Hund, N. Ackermann, J. Hohl-Ebinger, M. Schädel, W. Warta, and S. Winter, “Possible impact of systematic errors in IV-measurement,” in *23rd European Photovoltaic Solar Energy Conference and Exhibition*, 2008, pp. 1682–1686.

[9] ingun, “Test Probes Catalog 2010 / 2011,” 2010. [Online]. Available: http://www.ingun.com/en.

[10] J. Wong, “Griddler: Intelligent computer aided design of complex solar cell metallization patterns,” *Conf. Rec. IEEE Photovolt. Spec. Conf.*, pp. 933–938, 2013.