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CONTACTING BARE SOLAR CELLS FOR STC MEASUREMENTS

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ABSTRACT: Accuracy in the measurement of solar cell performance attains more and more economic significance additionally to its importance in technology development. Measurement of bare (without additional interconnectors on the bus bars) wafer based silicon solar cells directly in production with a high relative accuracy is important for cell sorting and a high absolute accuracy is necessary for valuation of the product. The calibration of the references used to set the cell testers focuses on the precision of I_{SC} measurement, but for the valuation the maximum power at standard testing conditions is the decisive number. Therefore the fill factor determination is a critical point which depends on the specific implementation of the four wire measurement technique. The paper discuses some contacting geometries in detail and proposes how to measure cell fill factor without interference of the bus bar resistance, because the bus bar is the interface to the cell ambience.
Keywords: Calibration

1 Introduction

With new solar cell production facilities exceeding the 100 MW limit, measurement uncertainties on the order of 1% for the output power of the cells produced are of high economic interest. Thus not only the accurate calibration of the irradiance at Standard Testing Conditions (STC,[1]) in cell testers, but also high precision in determining the fill factor (FF) on the bare cell (without interconnectors) is quite important. At the cell calibration laboratory of Fraunhofer ISE (ISE CalLab) the analysis and reduction of uncertainty components involved in the solar cell measurement at STC in testing laboratory as well as in industrial production control is a central topic.

Contacting the cell with four wire technique on the bus bar is in the cell calibration community well established. However, the design of the front contact grid is not standardized and on the contrary part of each manufacturer's specific cell design. Also the contact probe geometry usually differs between different measurement labs, because there is no generally agreed practice. But the contact probe geometry can have a strong influence especially on the measured fill factor (compare [2]).

This paper discusses different solutions for contacting the bus bar of bare solar cells. The number and position of the probes for current measurement influences the potential distribution on the bus bar, which depends on the bus bar conductivity as well. The position of a single voltage probe just measures one point of this distribution. The error depends on the geometry of the contacting unit and can reach values above 1 %.

The aim is to design the contact bar of the measurement system in a way that the uncertainty introduced by the contact geometry is independent of the bus bar conductivity. We investigated different possibilities in detail as a basis for precise calibration of bare solar cells. These considerations give an understanding of the influence of the contact geometry on FF measurement of bare solar cells, which is meant to form a basis for standardized contact geometry to achieve comparable FF measurements between different testing labs and industrial producers.

2 Contacting bare cells

2.1 Contacting with contact stripes and several current pins

In principle there exist different contact geometries as possible solutions for a four wire measurement. The number of contact pins and the position of the voltage pin(s) are decisive parameters. If we contact a bus bar of a 6" square solar cell (J_{MPP} = 30 mA/cm²) with a different number of current pins we can calculate the voltage drop across the bus bar (specific resistance assumed ρ= 3.2 10^{-8}Ohm m² in the example). In the model which we used to calculate the potential distribution on the bus bar metallization a spatially continuous current feed into the bus bar along it's length is assumed. In real cells the current feed-in will happen more in steps related to the metal fingers. In Fig 1 the results of the calculation of this potential distribution on the bus bar is given. The negative peaks are the positions of the current pins.

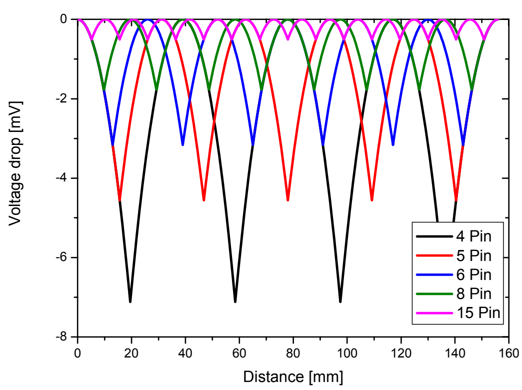


Fig. 1: Potential distribution on a bus bar of a 6" solar cell contacted with different number of current pins.

The position of the voltage pin(s) strongly influences the IV-curve measurement. For example at the maximum power point the measured voltage and the calculated FF is always too high, because the voltage drops monotonic towards the current pin position. The correct – bus bar independent - measurement needs a voltage measurement directly at the position of the current pin. Due to practical limitations a minimum distance of 2-3 mm appears to be realistic. In Fig 2 we calculated the deviation of the voltage measured in a variable distance in-between current and voltage pins compared to that directly at the current pin for the maximum power point for 4 (current) pins on 6" bus bar.

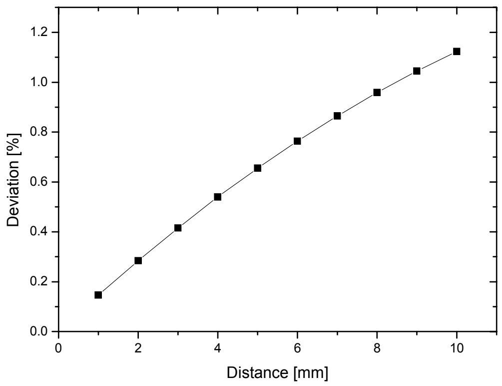


Fig. 2: Calculation for a contact system with 4 current pins on a 6" bus bar. The deviation of the measured to the real voltage at the maximum power point increases with the distance of the voltage pin to the current pin.

These deviations are errors in the calibration of bare solar cells which scale directly with the conductivity of the bus bar. For calibration purposes it is necessary to reduce this error to below 0.1 %. Then the dependence on the individual cell parameter (bus bar conductivity) is negligible. Fig 3 shows the deviation of the voltage measured at the voltage pin compared to that at the position of the current pin for 15 pins contacting a bus bar.

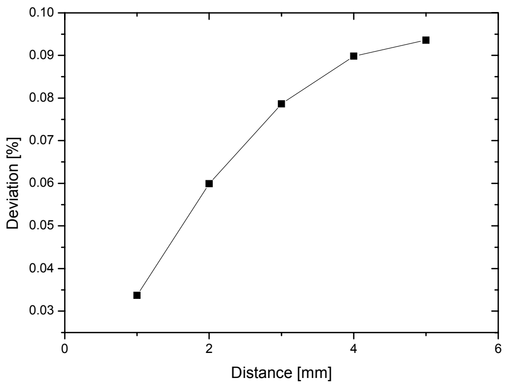


Fig. 3: Calculation for a contact system with 15 current pins on a 6" bus bar. The deviation of the measured to the real voltage at the maximum power point stays always below 0.1 %.

In order to contact the bus bar properly with several pins strips that hold the pins are necessary. These strips have to have low serial resistance interconnecting the current pins. The serial resistance has to be much lower than the bus bar resistance, otherwise the problems discussed above increase. Contacting the bus bars with strips is very common in the industrial environment. But these strips have the disadvantage that they cause shading on the measurement area. For well adjusted strips the shadow is mostly located at the bus bar metallisation, but shading small parts of the active cell area is unavoidable. On the other hand, the irradiance falling onto the strips may be reflected into other regions of the active cell. Taking both possibilities into account we will have shading losses and increased non-uniformity. If the shading is the same for the reference cell used to adjust the simulator and the device under test (DUT) we will have only a second order error because there is a directly correlation between both errors. The non-uniformity introduces deviations in fill factor and open circuit voltage [3].

2.2 Shading effects

The influence of the shading near the bus bar caused by a strip on the measured fill factor was estimated using a three dimensional distributed circuit model of an industrial-like silicon solar cell. For this purpose we used the circuit simulation program LTspice / Switcher CADIII [4].

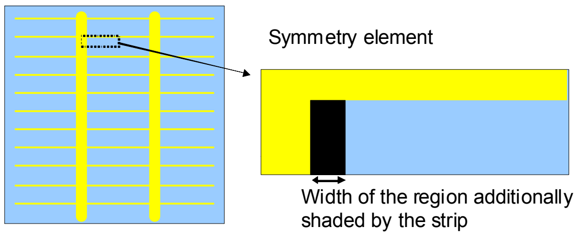


Fig. 4: Symmetry element used in the simulations to estimate the effect of additional shading caused by a strip.

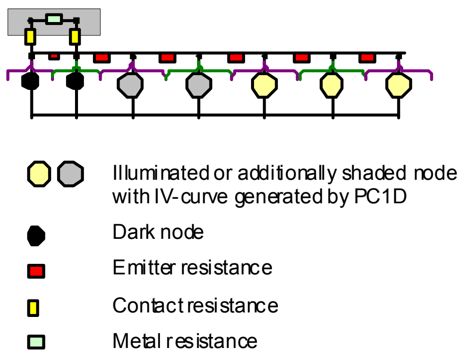
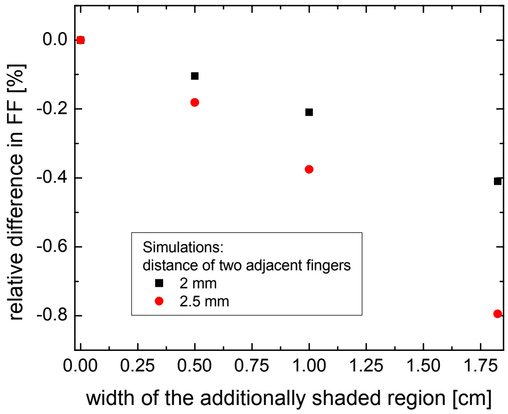


Fig. 5: Schematic of the distributed circuit model.

In Fig. 4 the symmetry element used in the simulations, in Fig. 5 a schematic of the distributed circuit model are shown.

To determine an upper limit of the effect of shading caused by a strip on the fill factor, total shading near the bus bar was assumed. The width of the region, which is additionally totally shaded near the bus bar, was varied. The current density of the un-shaded regions was increased according to the additionally shaded area in order to keep the short circuit current density of the whole symmetry element constant.

a)



b)

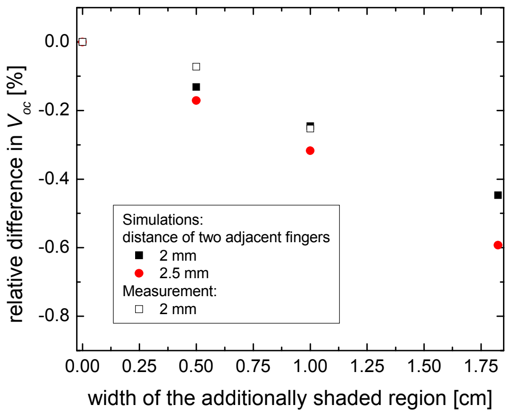


Fig. 6: Relative difference in fill factor (a)) and Voc (b)) between an industrial-type solar cell with and without additional shading. In the lower graph also measured data of an industrial silicon solar cell, on which the simulations are based, are shown. Further solar cell parameters are given in the text.

Fig. 6 shows the relative difference in fill factor and open-circuit voltage between a solar cell with and without additionally shaded region. The simulations were carried out for a solar cell with an emitter sheet resistance of 55 Ohm/sq, a total width of the symmetry element of 3.75 cm and a width of the bus bar on the symmetry element of 1 mm. In Fig. 6 b) also data measured on the cell, on which the model is based, are shown.
The results depend on the emitter sheet resistance and the distance of two adjacent fingers. In the analyzed cases a total shading near the bus bar results in an underestimation of the fill factor of less than 0.2 % relative for a width of the shaded region of 0.5 cm and of less than 0.4 % for a width of 1 cm.

2.3 Using non-shading Kelvin probes for I_{SC} determination

Using primary reference cells [e.g.WPVS] - usually done by accredited labs like ISE CalLab - the shading only occurs for the DUT. Therefore it has to be taken into account for the short circuit current (I_{SC}) measurement. The I_{SC} determination may be done with kelvin probes which introduce much less shading. In the measurements at ISE CalLab these probes contact the bus bar approximately 6 mm from the edge using 4-wire technique. For a standard metallised bus bar we calculate under I_{SC} condition the potential distribution shown in Fig 7.

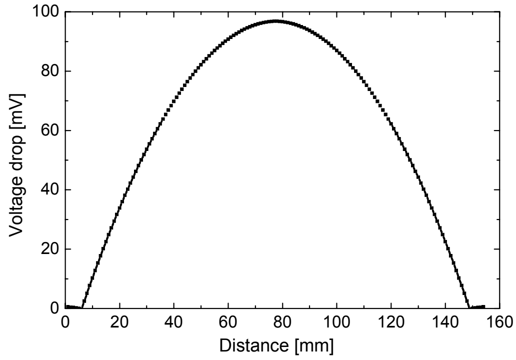


Fig. 7: Potential distribution on a 6“ bus bar contacted with two probes 6 mm from the edge.

This potential distribution can cause a non-uniform current distribution which depends on the shunt resistance (R_P) of the cell. With an appreciable shunt present the local current varies and the measurement gives in this situation approximately the mean value of the local currents. For cells with low shunt resistance this effect can be significant for the global measured I_{SC} value. Calculating this deviation (s. Fig 7) from expected I_{SC} in the simulation we will have deviations > 0.1 % with shunt resistance < 2000 Ohm cm². If we require that solar cells used as references should have shunt resistance higher than 2 kOhm cm², this effect is very small.

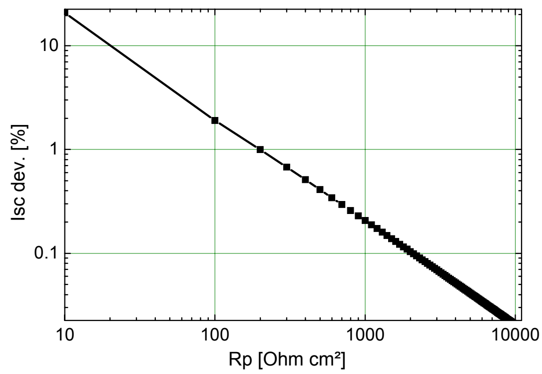


Fig. 8: I_{SC} deviation for a standard bus bar contacted with two probes 6 mm from the edge. The calculation uses the 2-diode model varying the shunt resistance (R_P) of the cell.

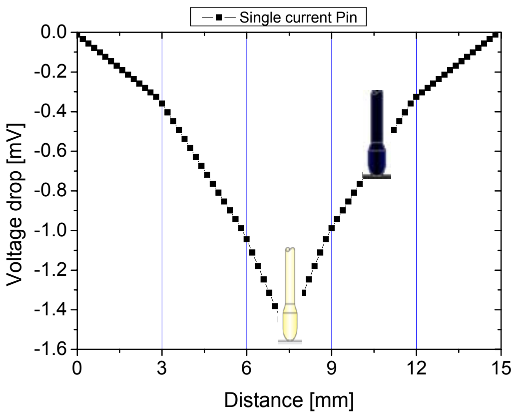
3 Voltage measurement with contact stripes

For the FF determination the task is the measurement of the voltage corresponding to a certain current. In four wire technique the voltage has to be measured at the point where the current leaves the measurement object.

3.1 Pin configuration

If we use a small distance between the current pins and minimize the distance between the current and the voltage pin we have reduced the systematic errors (see part 2.1). If we have pairs of current and voltage pins the position of the voltage pin next to the current pin has the drawback, that is the voltage is measured at the steepest part of the potential distribution (Fig 9 a)). That makes this configuration – although on a small level – sensitive for small changes in the current flow, maybe caused by differences in contact resistances for the various pins. To improve this it would be useful to have triples of pins and the voltage pin is in the current free point between to current pins (Fig 9 b)). Simulating small structures in the range of some millimeters we have to consider, that the current does not feed evenly into the bus bar but stepwise with each metallization finger (blue lines in Fig 9). We used a finger distance of 3 mm which is common for 6" solar cells. The geometry of the contact pins and the metallization fingers was chosen symmetrically to simplify the simulation. Other configurations will cause slightly different results but at the same order of magnitude.

a)



b)

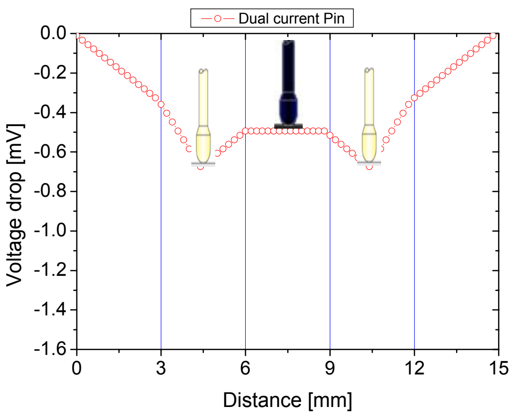


Fig. 9: Potential distribution for a single current pin and a dual current pin with a period of 15 mm. Distance to the voltage pin 3 mm. Metallization finger at blue lines feed current into the bus bar. Current pins are yellow and voltage pins are blue.

Placing the voltage pin in a current free region will be the best solution. If we position triples of pins a small distance apart and use the middle one as a voltage pin we can realize this situation for the symmetric arrangement used in the simulation. With a 15 mm pin interval we improve the voltage difference by a factor of 5 (from 0.2 % dev. to 0.04 % dev.).

3.2 Number of voltage pins

If we assume a uniform cell and uniform contacting of the cell we can use just one voltage pin close to one of the current pins. Deviations from such a uniform situation lead to a non-uniform voltage distribution and we have to measure an average value. This leads to the following configuration with several voltage pins.

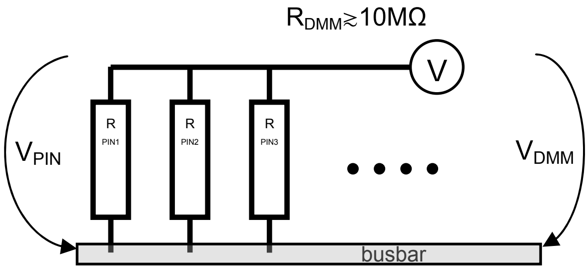


Fig. 10: Voltage pins on the bus bar interconnected to the measurement instrument (DMM).

$$U_{DMM} = R_{DMM} I_{DMM} = R_{DMM} \sum_i \frac{U_{PIN}}{R_{PIN,i}} \qquad \text{eqn 1}$$

Fig 10 shows the contact configuration for the voltage measurement. From eqn 1 one can see that for the global value (U_{DMM}) the single values (U_{PIN}) at each pin are weighted by the resistance of the single contact (resistance of contact, pin, wire…). To ensure a symmetrically weighting it is useful to add resistors to each single pin. An additional resistor of about 100 Ohm will dominate the circuit - contact, pin, wire - and not affect the accuracy of the voltage measurement. The additional voltage measurement error for a 15 pin configuration will be:

100Ω/15/10MΩ => 0.00007%

4 Conclusion

We have shown that the contact geometry has a significant influence on the fill factor measurement of bare solar cells without additional interconnectors on the bus bar metallization. The realization of a four wire measurement on the bus bar has to be free of the bus bar resistance. This bus bar free measurement uses the bus bar as the interface of the cell for the four wire technique. The aim is to reduce the deviation of the measured voltage to that on the position of the current pin below 0.1 % (of the V_{MPP}). This will be achieved with a current pin distance of about 10 mm and the voltage pin 3 mm to the current pin or with pairs of current pins (15 mm periodic) and the voltage pin in the middle. More than one voltage pin produces a mean value for non-uniform cells if similar resistances for the measurement loops are ensured.

5 Acknowledgement

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