

CONTACTING BARE SILICON SOLAR CELLS WITH ADVANCED CELL METALLISATION

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ABSTRACT: Improvements in cell metallization result in busbars with high resistance or of non-continuous or non-uniform geometry. Measurements of bare solar cells at calibration laboratories demand a procedure which is free of any influence of lab-specific contacting schemes. For most large area cells with front side contacts shadowing of the active cell area by the contacting unit during current-voltage measurements cannot be avoided. We present an advanced multiple step measurement procedure as performed at the Fraunhofer ISE calibration laboratory which is suitable for many actual metallisation schemes. We explain the requirements for the measurement setup and discuss the influence of contacting resistances. Insights are transferred to current-voltage measurements of cells with an unequal collection of current per busbar. For those cells, we propose a new measurement technique with adjustable resistors to enable homogeneous operating conditions across the cell. We demonstrate the influence on fill factor measurements with circuit simulations and validate our method experimentally with a specially designed solar cell.

Keywords: Calibration, Contact, Metallization, Performance, Qualification and Testing, Reference Cell

1 INTRODUCTION

The precise and traceable measurement of bare solar cells at Standard Test Conditions (STC) [1] is important for production line reference cells as well as for cell development evaluation in order to maintain international comparability. However, the exact way how to contact a wafer-based solar cell for a standard measurement is not covered by one of the IEC standards. Since the contacting can crucially influence the potential distribution in the solar cell, this can in the worst case lead to systematic differences in the results of a current-voltage measurement being much higher than measurement uncertainties from other sources. A standardised optimal contacting approach is necessary to achieve comparable measurements between different testing laboratories and industrial partners. This paper discusses measurement schemes and setups for precise short-circuit current I_{SC} and fill factor FF determination for cells with state of the art front side metallisation.

Referencing in a calibration lab is usually performed with encapsulated World PV Scale (WPVS) cells and is therefore not affected by contacting units. The calibration of large area cells with front side contacts for the use as references in a production is, however, done with complex contacting units to guarantee homogeneous operating conditions across the cell. As a result, inhomogeneous illumination, e.g. shadowing, can normally not be avoided. The general influence of the contacting unit on the illumination depends on the geometry of the metallization, of the contact unit itself and the measurement light beam divergence of the utilized sun-simulator. Therefore, optimum inter-comparability is achieved if the calibration procedure for bare cells essentially eliminates the influence of the contacting unit on the illumination.

Since for our measurement setup shadowing is the largest contribution to the inhomogeneous illumination we refer to the outcome of the correction procedure as a shadow-free measurement. For state of the art cells the standard approach cannot always be applied. To give an example of our advanced measurement scheme the procedure is performed on a cell with highly resistive busbars.

A possible source of error is identified to be differing voltage drops across the load paths to the cell contacts.

Differing voltage drops can be caused by unequal contact resistances or unequal currents per busbar. Our solution to the problem is a balancing contacting scheme with adapted resistances as proposed by Sinton [2].

The identical situation occurs during IV curve measurements for cells which are designed to have different current output per busbar [3]. Not using an adjusted balancing contacting scheme has crucial impact on fill factor measurements making both over- and underestimation possible. We demonstrate the effects with circuit simulations and measurements of a cell designed with asymmetric current collection.

2 FUNDAMENTALS

2.1 Temporary contacting of bare solar cells

Generally, our goal of contacting wafer based silicon solar cells for current-voltage measurements is to achieve an equal and uniform potential on all designated contacting bars. In that case the measured cell characteristics simulate optimal cell integration into a module, i.e. perfectly conducting cell interconnectors covering all contact regions of the cell without shadowing the active cell area. The resulting current is obviously not equal to the one which can be obtained in module application, but allows a straightforward and, most importantly, traceable conclusion to the cell performance in the module, once the cell-to-module loss is determined.

A few measures taken to realize an optimal electrical contacting are explained in [4] and adopted as standards in calibrated measurements at the Fraunhofer ISE calibration laboratory. The main points are shortly summarized:

- Best voltage sensing can be achieved with the four wire measurement using triples of pins, i.e. dual current pins (distance 3 mm) with one voltage pin in-between.
- Additional resistors of 100 Ω for each voltage pin dominate the circuit resistance, e.g. contact and wiring resistances, and therefore lead to arithmetic weighting of the voltages measured at the pin contacts.
- For most standard cells a distance of less than 12 mm between load pins is sufficient for a

homogeneous potential on the busbar.

- If the additional shadow caused by the contacting unit extends up to 0.5 cm from the busbar the relative fill factor error in a measurement is less than 0.2 % compared to a measurement without shadowing and the same short-circuit current.

2.2 Standard approach of shadow-free measurements

In particular the last point enables a short-circuit correction for large area cells with the standard approach described in detail in [4]. Basically, a second short-circuit current measurement is performed with Kelvin probes contacting the busbar ends and casting insignificant shadow. The measurement steps for the shadowing effects of a contacting unit for a measurement under standard testing conditions (STC) are as follows:

- The short-circuit current I_{SC} is measured with a contacting unit which introduces negligible shadowing for an illumination of 1000 W/m^2 after mismatch correction (IEC 60904-7).
- A contacting unit leading to optimal electrical contacting but with a certain unavoidable shadowing is used to measure the I_{SC} a second time.
- A third measurement with the same contacting unit as in (ii) and adapted illumination intensity to correct for the shadowing effect is carried out to determine the cell performance at STC.

For standard cells a voltage drop of about 100 mV from the middle to the end of the busbar was simulated in [4] and the conclusion given that the short-circuit current measured with this configuration is correct within 0.1 % for cells with parallel resistances higher than $2 \text{ k}\Omega\text{cm}^2$.

3 ADVANCED APPROACHES TO SHADOW FREE MEASUREMENTS

Since the geometry and characteristics of the cell metallisation on crystalline wafer-based solar cells changes due to cost reduction efforts or improvements in material and cell concepts the above mentioned assumption concerning the voltage drop over the busbar is not always valid. This is especially true for cells having busbars with high resistance as, e.g., hetero-junction solar cells with low-temperature firing pastes. Also cells having busbars of non-continuous or non-uniform geometry demand the contacting pin configuration to be adapted to the busbar characteristic to guarantee homogeneous potential.

3.1 Advanced approach 1

Depending on the geometry and resistance of the busbar metallization, the potential distribution on the busbar during the I_{SC} measurement can reach differences in the range of 200-400 mV with shadow free Kelvin probe contacts near the busbar ends. This is shown in Fig. 1 for a selection of five cells with continuous and non-continuous busbars.

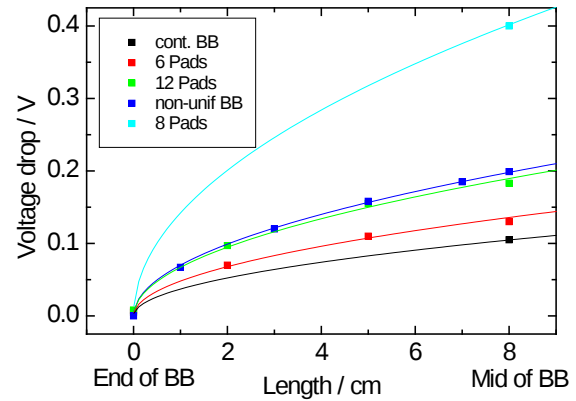


Figure 1: Measured voltage drop over the busbar (BB) during the measurement of I_{SC} when contacting with Kelvin probes at the BB ends (cell selection: continuous busbar, non-continuous busbar with 6, 8 or 12 pads, non-uniform busbar). The curves are root functions as a guide to the eye.

For cells having busbars with sufficient length and conductivity, a system of Kelvin probes as shown in Fig. 2 can be used to homogenise the potential. This contacting system does produce significant shadowing on the surface of the cell, which can be estimated by comparing the measurement with just 6 Kelvin probes and the measurement with the additional current probes installed but not electrically connected to the electronics. Thus, the shadow can be compensated for by adjusting the intensity for the final measurement. Intermediate data of the measurement procedure is shown in Tab. I for a cell with 8 contact pads and highly resistive busbar. The voltage difference on the busbar during the I_{SC} measurement can be reduced from initially 400 mV with 6 kelvin probes to 90 mV using the additional current probes. Without this procedure, the I_{SC} would be underestimated by about 0.35% for the present cell.

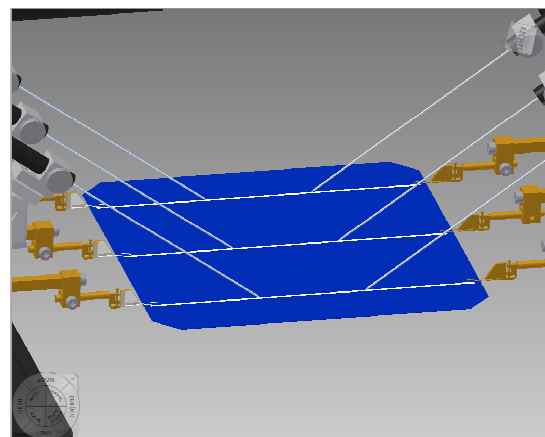


Figure 2: Contacting a bare solar cell with 6 kelvin probes on each end of the busbar and 6 additional current probes placed 54mm from the ends. This contacting reduces the non-uniformity of the potential distribution during I_{SC} measurement.

Table I: Intermediate data for an example I_{SC} measurement with 6 Kelvin probes and 6 additional current probes. The maximum voltage difference on the busbar ΔV is reduced to 90 mV.

Step	ΔV [mV]	Configuration	Percentage of I_{SC} value	FF [%]
1	400	6 Kelvin probes (KP)	99.65	44.95
2		6 KP + 6 additional probes (not electr. contacted)	99.01	44.44
3	90	6 KP + 6 additional probes (electr. contacted) + shadow correction of add. probes	100.00	70.31
4		Contact unit	95.82	77.09
5		Contact unit + shadow correction	100.00	77.12

Although the additional shadow can be corrected sufficiently for most cells with non-uniform busbars, a homogeneous potential on the cell cannot be guaranteed in the case of non-continuous busbars. Therefore, we propose a different method to correct the shadowing effect.

3.2 Advanced approach 2

If the solar cell has at least three busbars, we can contact the cell with two contact bars and two Kelvin probes first, see contact situation in Fig. 3. The potential distribution is uniform enough for most solar cells, even for cells with non-continuous and non-uniform busbars. This can easily be verified by measuring the voltage drop from the busbar ends to a position on the busbar where the highest difference is expected.

The voltage drop should be below 100 mV. Then, the same conditions regarding the parallel resistance apply as stated in [4] and above, namely that the parallel resistances should be higher than $2 \text{ k}\Omega\text{cm}^2$. If necessary, the additional current probes, see Fig. 2, can be used to further increase the homogeneity of the potential.

Secondly, we exchange the two Kelvin probes with a contact bar and compare the measured I_{SC} values in order to determine the influence of the shadowing. This method is used for each busbar separately to get the overall shadowing effect and compute the shadow free I_{SC} :

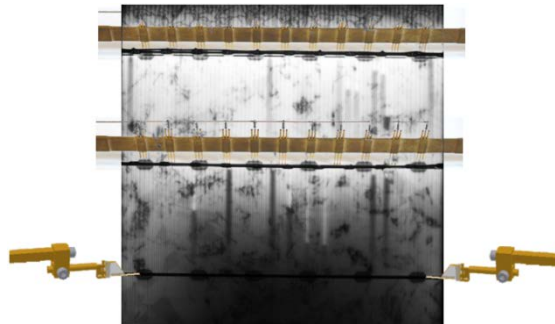


Figure 3: EL image of a mc-Si solar cell with three continuous busbars in H-pattern design contacted with two contact strips on the upper two busbars and with Kelvin probes on the ends of the bottom busbar. The potential around the middle of the bottom busbar is decreased due to series resistance.

$$I_{sc}^{sf} = I_{sc}^3(1 + 2 + 3) + [I_{sc}(2 + 3) - I_{sc}^1(1 + 2 + 3)] + [I_{sc}(1 + 3) - I_{sc}^2(1 + 2 + 3)] + [I_{sc}(1 + 2) - I_{sc}^3(1 + 2 + 3)] \quad (1)$$

$$I_{sc}^{sf} = I_{sc} \text{ shadow free}$$

$$I_{sc}(2 + 3) = I_{sc} \text{ measured without contact bar 1}$$

$$I_{sc}^i(1 + 2 + 3) = I_{sc} \text{ measured after the final positioning of the contact bar } i.$$

In total six measurements are necessary, respectively four if a reproducible mounting of the contacting bars can be guaranteed, leading to

$$I_{sc}^1(1 + 2 + 3) = I_{sc}^2(1 + 2 + 3) = I_{sc}^3(1 + 2 + 3).$$

3.3 Requirements for measurement setup

The following considerations regarding the load contacting scheme can best be motivated with a simple example: The method described above can in principle also be used for busbarless cells with a few adjustments. First, a contacting bar is needed which contacts all fingers and enables balancing voltage measurement. Secondly, a higher number of contact bars compared to a standard H-pattern design might be necessary since the Kelvin probes cannot be used to establish a sufficiently uniform potential. If then the procedure described by eq. 1 is applied the area percentage which a contact bar is supposed to drain of current is not equal for all contact bars. Assuming comparable contact resistances per contact bar as well as external resistances, the voltage drop from the terminal to the cell surface differs for the contact bars. During terminal I_{SC} conditions the individual contact bars do no longer establish local I_{SC} conditions on the cell. Hence, we propose to use adjustable resistors to equalize the local potential between busbars.

The same situation occurs for standard H-pattern cells if a combination of contact bars and Kelvin probes which have unequal contact resistances is simultaneously used. For these cells we propose to use equal balancing resistances which dominate the circuit resistance in order to obtain equal current output per busbar.

4 FF MEASUREMENT OF CELLS WITH ASYMMETRIC CURRENT COLLECTION

This consideration becomes even more important for cells which are designed to have unequal current output per busbar. Usually, due to the high conductivity and the low contact resistance of the cell interconnectors the cell performance in the module is not influenced by this asymmetry. However, this is different for temporary contacting. Not using an adjusted balancing resistor scheme for the load contacts distorts fill factor measurements, as will be shown in this chapter.

4.1 Measurement setup

Distorted fill factor measurements and the correction procedure with adjustable resistances are demonstrated with the cell shown in Fig. 4.

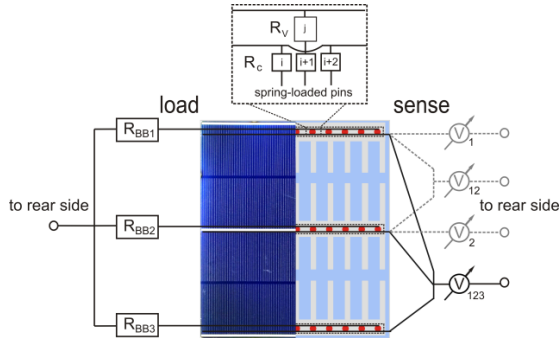


Figure 4: A specially designed cell having approximately twice the current output at the inner busbar compared to each outer busbar. Resistors R_{BBi} can be added to the load paths and the voltage can be measured with different sense configuration.

The front side metallisation is designed with non-continuous fingers to give a current collection ratio between inner and each outer busbar of approximately 2:1. The inset shows a triple of spring-loaded pins of the contact bar with a voltage pin in-between two current pins according to paragraph 2.1. All pins have an individual contact resistance R_c and the voltage pins have additional balancing resistors R_v of 100 Ω . Cable resistances and unavoidable resistances of the external circuit are not shown. An additional resistance R_{BB} can be added to each load path contacting the busbars. The four wire voltage measurement can be done with different contact combinations: either the voltage of a single busbar is taken as reference or a combination of two, respectively all busbars.

4.2 Circuit simulation

A circuit simulation was performed with LT Spice [5] using the symmetry element shown in Fig. 5. The element measures 7.8 cm in y-direction and 0.61 mm in x-direction corresponding to a 6-inch cell format and a finger distance of 1.22 mm. To reproduce different measurement setups, additional resistors R_{BB1}^* and R_{BB2}^* are integrated to the load paths before the busbars are short-circuited. Two adaptations are made compared to the resistances in Fig. 4 to enable direct comparability between measurement and simulation. First, to realize equal voltage drops, the resistance R_{BB1}^* is the resistance R_{BB1} multiplied by the number of symmetry elements constituting the full cell. Secondly, since BB2 carries double the current produced by the configuration in the symmetry element, this factor is additionally applied to R_{BB2}^* . In the simulation the voltage can directly be taken from the busbars to test different sense configurations.

A simplified approach with standard parameters for the circuit elements resembling an industrial-like cell was chosen. Only the short-circuit current density J_{sc} with 39.2 mA/cm² for the illuminated nodes and emitter sheet resistance with 90 Ω /sq were matched to the exemplary cell. The further parameters are as follows: Dark saturation currents J_{01} and J_{02} are 1e-12 A/cm² and 1e-18 A/cm² with ideality factors of one and two, respectively. The shunt resistance was chosen to be 10 k Ω cm², contact resistance 5 m Ω cm² and metal resistivity 3e-6 Ω cm. Finger and busbar height is 16.2 μ m, width is 40 μ m and 1.5 mm, respectively, and the finger pitch is 1.22 mm.

The number of nodes per circuit element was chosen

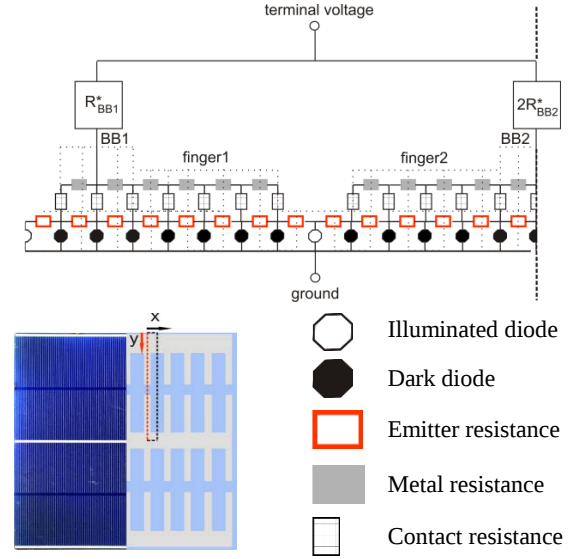


Figure 5: Schematic illustration of the simulation domain along the y-axis.

with a sensitivity analysis according to Tab. II.

Three load contacting schemes were simulated: The first one has built-in resistors of 10 m Ω to resemble a typical non-perfect contacting in a measurement setup, where the resistance is caused by the contacting resistance of the contact bar and the external load wiring to the amperemeter. The second configuration has built-in resistors of 100 m Ω , which dominate the contacting or wiring resistances of scheme one. The third scheme has built-in resistors which are adapted to the ratio of total short-circuit current to current per individual busbar at ideal I_{sc} conditions:

$$R_{BBi}^* = c \cdot \frac{I_{tot}}{I_{BBi}}, \quad (2)$$

with the proportionality constant c , which should be chosen so that the resistances outweigh all unavoidable circuit resistances as, e.g., pin contact resistances.

For each load contacting scheme different sense configurations for voltage measurement were simulated as indicated in Fig. 4.

For comparison, in a previous study Schinke *et al.* examined the contacting for an interdigitated back-contact (IBC) solar cell with four busbars having asymmetric current collection for busbars of the same polarity [3]. Their study includes a variation of pin contact resistances and cable resistances. The latter is in principle similar to our contacting schemes I and II. They concluded that all resistances in the contacting circuitry should be kept as low as possible and recommended to always indicate the sensing scheme of the measurement when stating IV-curve parameters of the studied cell design. Otherwise fill factors would not be meaningful.

Table II: Number of nodes used for the elements of the simulation domain, see Fig. 5.

Direction	Element	Number of nodes
y	Finger	150
	Gap / active area	8
	Full BB	12
x	Finger	4
	Active area	8

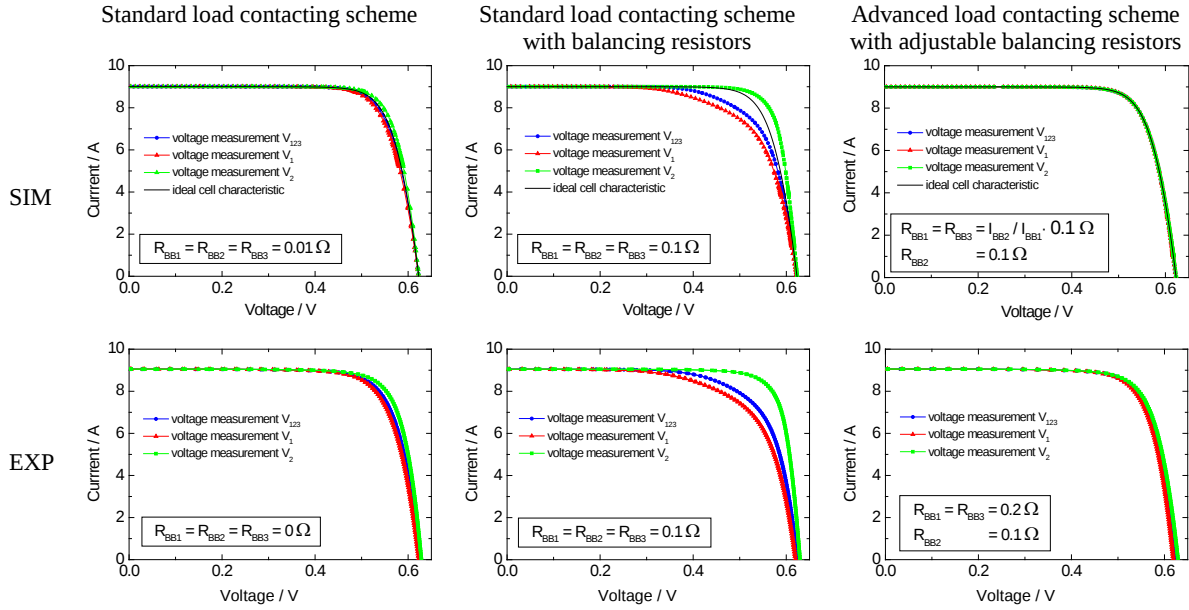


Figure 6: Simulated and measured current-voltage characteristics for different combinations of balancing resistors and voltage measurement schemes. The standard load contacting distorts the fill factor measurement due to unavoidable contact and wiring resistances. Only a scheme with adjusted resistances can provide equal potential on the busbars.

4.4 Results and discussion

Simulated and measured current-voltage characteristics for the three load contacting schemes are shown in Fig. 6 for different voltage sensing. The corresponding fill factors from the simulation are shown in Tab. III.

The ideally measured fill factor, abbreviated here as ideal FF , is simulated to be 78.50 % and does not depend on the sensing scheme. Introducing a resistance of 10 m Ω for all busbars leads in the best case with balanced sensing of all busbars to a FF deviation of 0.42 % absolute. If the circuit resistances are not approaching zero the local potential on the busbars will differ, hence, sensing with BB1 always underestimates the ideal FF and sensing with BB2 always overestimates the ideal FF . By defining limitations for the circuit resistances the absolute fill factor deviation can be sufficiently reduced, but this makes it necessary to know the actual resistances of the measurement circuit. Furthermore, since the cell is not in its optimal operation condition, this approach is susceptible to faults and instabilities of the measurement setup. For comparison a measurement without implementation of additional resistances is also shown in Fig. 6. The only resistances are caused by the contacting bar, cables and connections, e.g. using banana connectors.

The second simulation describes a load contacting scheme with implemented balancing resistors of 0.1 Ω .

Table III: Simulated fill factors for measurement schemes with different load contacting and sensing.

Load contacting scheme	FF_1 / % with V_{BB1}	FF_2 / % with V_{BB2}	FF / % with all BB
Ideal	78.50	78.50	78.50
I	76.99	79.81	77.92
II	66.55	82.11	70.35
III	78.56	78.47	78.53

As stated in paragraph 3.2 to be proven with the next contacting scheme, this scheme is optimal for solar cells with equal current output per busbar. It reduces the influence of contact resistances which, in practice, cannot be guaranteed to be equal for each busbar. Using this for symmetric cells optimized contacting scheme for asymmetric cells leads to strong deviations in FF . Note that the same considerations apply to the shadow correction procedure described in chapter 3 when measuring a symmetric cell with asymmetric contacting.

The third contacting scheme leads to correct FF measurements since all busbars are on equal potential. This approach is therefore less dependent on the sensing scheme. The small deviations in the simulated FF are caused by approximation of the current ratio in eq. 2.

4.5 Practical implementation

During the short-circuit measurement under a steady-state sun simulator the voltage difference between busbars can easily be measured. By implementing one constant resistor and using potentiometers the voltage difference can be reduced to approach zero. Then, the potentiometer automatically fulfils eq. 2 and the actually intended ratio of current output per busbar must not be known.

4.5 Module interconnection techniques

Solar cell characteristics measured in the way described above reflect optimal cell integration into a module. This means perfectly conducting cell interconnectors covering all designated contact regions of the cell without shadowing the active cell area. For interconnection concepts with non-negligible resistances the module performance can potentially be optimised if the interconnections are designed with resistances according to the ratio of busbar currents, eq. 2. If this goal can only be reached by implementation of additional resistances, it should be assessed if the power gain in homogenizing the cell potential outweighs power losses

by Joule heating.

4.6 Conclusions

Improvements in cell metallization demand adjustments of standard approaches to measure correct current-voltage characteristics of bare solar cells. The short-circuit current of cells having busbars with high resistance or of non-continuous or non-uniform geometry can be determined with an advanced multiple step measurement as performed at the Fraunhofer ISE calibration laboratory. The advantage over previous methods is a more homogeneous potential distribution over the busbars.

For the measurement of current-voltage curves we recommend to use balancing resistors for the load paths which dominate the contact resistances and are adjusted to the current ratio the busbars are supposed to drain. Otherwise, the cell can have ambiguous operating conditions leading to measurement errors. This is especially true for cells with asymmetric current collection per busbar. As a result of the proposed contacting scheme measurements are less sensitive to voltage sensing than without any adjustments. Therefore, measured fill factors are meaningful without stating the sensing scheme.

The proposed method can easily be integrated into standard measurement systems.

ACKNOWLEDGMENT

This work was funded by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (Contract Number 0325447 OHM).

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