Precise and accurate solar cell measurements at ISFH CalTeC

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Abstract

This paper presents the calibration of solar cells, in accordance with the IEC 60904 standards, carried out at the solar cell calibration laboratory of the Calibration and Test Center (CalTeC) at the Institute of Solar Energy Research Hamelin (ISFH). For the calibration of a solar cell, the cell area, the spectral responsivity (SR) and the current–voltage (*I*–*V*) curve have to be determined. The *I*–*V* curve then yields the characteristic parameters, including the power conversion efficiency, fill factor, short-circuit current and open-circuit voltage. The required measurement facilities and contacting stages are explained in detail; in addition, the measurement procedures are introduced. The precision and accuracy of the resulting characteristic parameters and curves are demonstrated by recent intercomparisons between different international calibration laboratories.

Introduction

As stated in the PV Status Report 2018 published by the European Commission [1], the global investment in 2017 to install about 100GW of solar PV power was €140bn. PV products are currently priced according to their power output measured under standard testing conditions (STC); thus, every per cent uncertainty in output power measurements LEADS to a financial uncertainty of around €1.4bn. Consequently, a precise measurement of PV devices in accordance with worldwide standards and traceable to SI units is of utmost importance. Calibration laboratories play a major role in this value chain, providing reference solar cells as standards for the calibration of solar simulators in laboratory and production environments.

For this purpose, the solar cell calibration laboratory of the Calibration and Test Center (CalTeC) at the Institute of Solar Energy Research Hamelin (ISFH) is accredited for the calibration of solar cells as defined in the IEC 60904 standards. The scope of accreditation includes:

- The area A of the cell or the aperture mask used for measurement.
- The spectral responsivity (SR) of the cell.
- The characteristic parameters of the current–voltage (*I*–*V*) curve (short-circuit current I_{sc}, open-circuit voltage V_{oc}, fill factor *FF* and power conversion efficiency η).
- The temperature coefficients α (for I_{sc}), β (for V_{oc}) and δ (for P_{max}).

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Recently, the scope of accreditation was extended to include irradiance sensors as test objects too. For these sensors, ISFH CalTeC certifies the output signal (a voltage or a current) at a defined irradiance (e.g. 1,000W/m^2) and a defined temperature (e.g. 25°C).

All parameters are reported with the accompanied uncertainty following an approved measurement uncertainty analysis. In order to ensure traceability to SI units, all reference devices are calibrated at Physikalisch-Technische Bundesanstalt (PTB) – the National Metrology Institute of Germany. The accreditation is carried out by **D**eutsche **Akk**reditierungs**s**telle (DAkkS) – the national accreditation body of the Federal Republic of Germany – under the registration number D-K-18657-01-00. It has been confirmed that ISFH CalTeC fulfils the ‘General requirements for the competence of testing and calibration laboratories’ of the International Organization for Standardization in ISO/IEC 17025.

Besides providing reference solar cells, calibration laboratories also act as independent bodies in confirming record efficiencies. Record efficiencies are listed most prominently in the regularly published ‘Solar cell efficiency tables’ (see, e.g., Green et al. [2]) in the international journal *Progress in Photovoltaics* (Wiley) as well as in the continuously updated ‘Research cell record efficiency chart’ [3] provided by the National Renewable Energy Laboratory (NREL). ISFH CalTeC is listed as one of seven ‘designated test centres’ participating in international round robins to demonstrate their required measuring accuracy and international comparability in measuring record efficiencies [4]. In three recent international intercomparisons [5–7], ISFH CalTeC showed excellent agreement with the other participants, indicating a high measurement accuracy and precision.

Here, insights into the calibration equipment used at ISFH CalTeC are given, and details of the calibration procedures are presented.

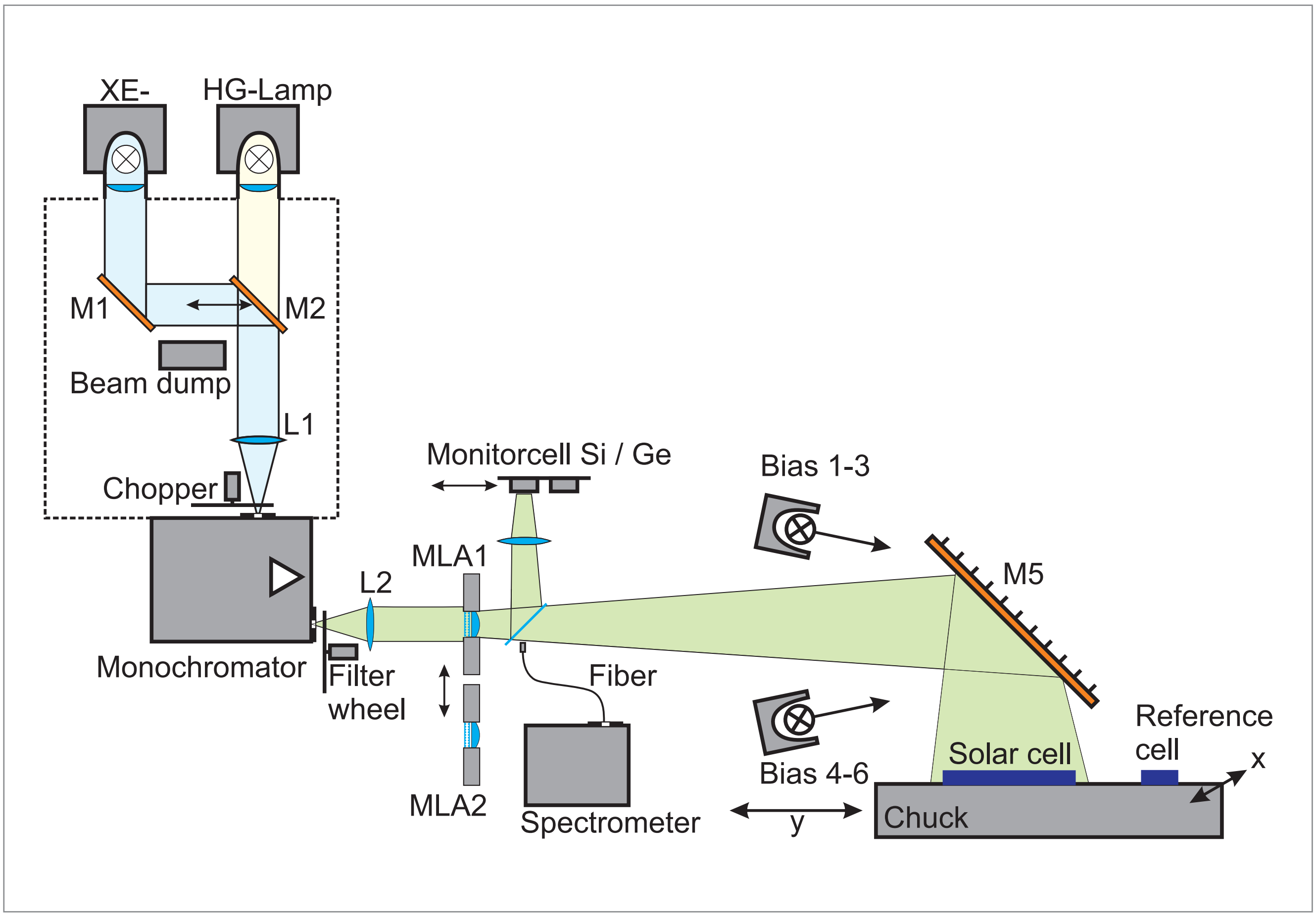

Figure 1. Schematic of the spectral responsivity measurement facility. Mirrors are labelled M while lenses are labelled L. By means of two micro-lens arrays (MLAs), monochromatically irradiated areas of 40×40 and 180×180mm² are realized. The chuck is mounted on an *x*–*y* stage that allows either the reference cell or the solar cell under test to be irradiated.

Equipment

Three main measuring systems are required for the calibration of solar cells: one to determine the active area, another to determine the spectral responsivity, and a third one to measure the *I*–*V* characteristics.

Area measuring facility

The area of the solar cell under test (DUT) is of utmost relevance, since this value is required for calculating the energy conversion efficiency. CalTeC's area measurement system consists of a document and photo scanner which has a resolution of up to 9,600 dpi and is calibrated by means of a photolithographic-defined glass–chrome mask. Depending on the size of the object, expanded measurement (k = 2) uncertainties as low as 0.4% are obtained; for typical industrial solar cells with an area around 240.0cm², this uncertainty corresponds to an area of 0.96cm². The calibration of the glass–chrome mask is carried out by the National Metrology Institute of Germany (PTB).

Spectral responsivity measuring facility

The spectral responsivity of the solar cell under test is required for the calculation of the spectral mismatch factor *MM*, which compensates for differences in the current generation between the target spectrum (usually AM1.5G) and the spectrum of the sun simulator used for the measurement of the *I*–*V* characteristics.

Fig. 1 shows a schematic diagram of the differential spectral responsivity (DSR) facility developed in-house. The set-up consists of a two-beam assembly irradiating the entire solar cell under test simultaneously with white bias light and monochromatic probe light. The monochromatic light is generated using a grating monochromator into which the light of either a xenon or a halogen lamp is coupled. A homogeneous monochromatic illumination in the test plane with an inhomogeneity below 2% for most wavelengths is realized with the help of micro-lens arrays (MLAs), allowing areas of either 40×40 or 180×180mm² to be illuminated. The remaining inhomogeneity is measured at 64 homogeneously distributed positions by shifting a world photovoltaic scale (WPVS) [8] reference cell in 20mm steps in the *x* and *y* directions. A precise knowledge of the light field homogeneity is essential, since it is necessary to correct for differences in monochromatic light field intensities between the position of the reference cell and the mean value of the large light field. An array of 48 halogen lamps allows bias light intensities of up to 1,600W/m² (1.6 suns) to be obtained. The current generation due to the monochromatic light at the different bias irradiances is measured by means of a lock-in approach. The monochromatic light intensity is modulated using a mechanical chopper at the entrance slit of the monochromator. A transimpedance amplifier developed in-house keeps the solar cell under short-circuit conditions and outputs a voltage signal proportional to the current generated by the monochromatic light. The output signal is then measured with a lock-in amplifier. WPVS reference solar cells calibrated at the PTB are used for calibrating the DSR facility.

I–V curve measuring facility

I–V measurements are carried out using the light from a class AAA solar simulator (WACOM WXS-156 S-L2), shown in Fig. 2. The system comprises a two-lamp system (halogen and xenon) with a light field area of 175×175mm^2 and is thus compatible with wafer formats up to M6. The inhomogeneity is less than 2%, the long-term instability is under 1%/hour and the divergence (collimating angle) is below 3%.

For the compensation of short-term intensity fluctuations, the solar simulator is equipped with a monitor device and a fast feedback loop. The solar simulator is also equipped with a fast shutter unit, which is used to determine the 25°C-equivalent open-circuit voltage ($V_{oc,eq}$) from the open-circuit voltage measured as a function of time after opening the shutter [9]. A spectroradiometer, a contacting unit for the device under test (DUT) and a WPVS reference solar cell are mounted on a motorized *x* axis; this set-up allows a precise and fast control of the intensity and the spectrum of the solar simulator.

The solar cell measurement unit is equipped with a *z* stage to allow the compensation of contacting chucks of different thicknesses. The measurement unit consists of different components stacked on top of each other. At the bottom, there is a water flow cooling plate, which acts as a re-cooling unit for the array of 16 Peltier elements placed above. Positioned on top of this is a base plate to which different contacting plates can be screwed, depending on the cell type to be investigated. The device temperature can be adjusted to values between 20 and 80°C, allowing reliable measurements of the solar cell temperature coefficients. The contacting to the solar cell is implemented as a four-wire configuration.

A four-quadrant power supply is used for the measurement of the solar cell *I–V* curve. The current is measured by means of a voltage measurement across calibrated high-power precision shunt resistors. The measured values for voltage, current and temperature are recorded by separate and externally triggered calibrated multimeters. Both n- and p-type solar cells with edge lengths between 20 and 175mm and short-circuit currents of up to 15A are measured.

Figure 2. CalTeC's *I–V* curve measurement facility. A sun simulator provides a class AAA solar spectrum, while an *x–z* stage allows irradiation of the reference cell, the spectral radiometer or the solar cell under test.

Contacting units (front and rear)

No explicit standard exists for the design of the solar cell contacting scheme. The IEC 60904-1 recommends a four-wire connection at the cell busbars, and a note in this standard states that it is advisable to choose the contacting method appropriate to the intended use of the cell or of the measurement.

The design of contacting units that yield precise and accurate measurements of the solar cell *I–V* characteristics, however, represents one of the major challenges in solar cell calibration. Contacting units must be continuously developed to adapt to new metallization designs. For contacting the solar cell front busbars, some authors [10,11] demand a contacting method which reflects the module integration, while others [12,13] recommend a contacting scheme with an infinite number of contact points, thus neglecting the resistivity of the busbar.

Various contacting schemes are available. In order to contact the customer's cells as accurately as possible, the most suitable options are determined together with the customer. The contacting method used for the certified measurements is described in detail on the calibration certificate. In general, it is assumed that there is an infinite number of contact points on the area provided for the purpose of contacting, yielding the fill factor FF_{infcp}. This definition

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enables reproducible measurements between different laboratories and measuring facilities, without explicitly defining the specific contacting scheme; it can also be extended to busbarless solar cells, where the area provided for the purpose of contacting are the fingers. Every real contacting scheme can only be an approximate solution to this. A potential distribution forms between two adjacent contact points and depends on the amount of current flowing and the conductivity of the metallization. It has been shown [14,15] that placing the sense contact at a certain distance from the current contacts yields the reference fill factor FF_{infcp}, even for very low-conductive busbars or fingers. Series resistance effects of the busbars or fingers are effectively cancelled out. A recent study on the impact of the contacting layout on the measured solar cell fill factor [14,15] shows that the best position for sensing corresponds very well to probing the average potential between two current contacts.

For solar cells with an edge length of approximately 156mm, a triplet structure with the voltage pin positioned between two current-carrying pins is used. In order to keep the mechanical load to a minimum, five triplets are homogeneously distributed over the busbar. Each single contact is realized by a spring-loaded contact pin, which is mounted in a 2.5mm-thick vertically positioned printed circuit board (PCB). When the aim is to contact thin busbars of widths smaller than those of the contact probes, the most reliable results are obtained when using probes with a multi-crown head. In all cases, the additional shading of the cell needs to be kept to a minimum in order to minimize the impact on fill factor [16]. Thus, for contacting the front of multi-busbar cells comprising up to 12 busbars, thin contacting bars with an overall thickness of just 0.8mm have been developed (Fig. 3). The contact is made by means of copper sheets, into which a structure is cut that has a certain spring action.

A full-area brass chuck, shown in Fig. 4(a), is available for contacting the rear side of a solar cell; this particular chuck has integrated vacuum grooves to hold down the cell. In contrast to typical full-rear-area contacting plates, a sensing pin is intentionally not used here; instead, a sensing segment that is glued into the measuring plate is employed. This form of sensing was consciously chosen in order to be able to measure solar cells that are mechanically sensitive, which is often the case for cells comprising stacks of dielectric layers on the rear. Moreover, this contacting plate allows the contacting of the rear of bifacial solar cells, including busbarless bifacial solar cells.

A non-conductive chuck, shown in Fig. 4(b), is also available to allow the local contacting of the rear of bifacial solar cells. Electrical contact to the busbar is established by spring-loaded contact probes; these probes are located in the same positions as the front probes in order to minimize mechanical stress to the cell. The current design of this chuck is optimized for the measurement of solar cells with five busbars. To change the reflectivity of the chuck, optional plates are available.

Solar cell calibration procedure

There are three tasks involved in the standard method for taking a calibrated solar cell measurement: 1) measure the solar cell area or the area of the mask used to define the active area; 2) measure the DSR; and 3) measure the *I–V* characteristics.

(a) (b)

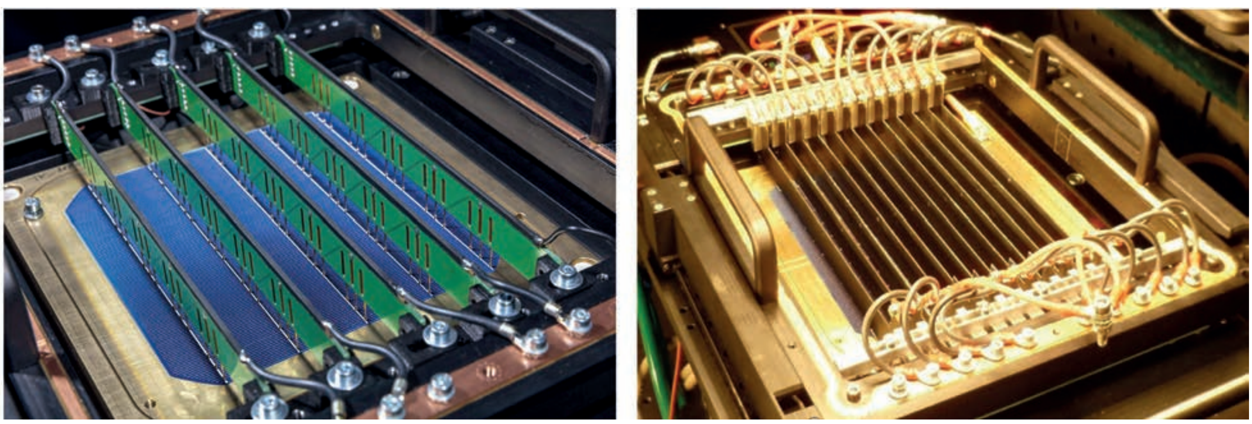

Figure 3. (a) Standard 2mm-wide contacting bars with spring-loaded contact pins for contacting solar cells with up to six busbars. (b) Thin 0.8mm-wide contacting bars for contacting solar cell with up to 12 thin busbars.

Area measuring procedure

The area measurement is a comparative measurement. In a first step, a photolithographic-defined segment of a chrome–glass mask reference sample is scanned. The sharp edge of the photolithographic-defined segment yields a scanned image with a well-defined edge. By means of a predefined threshold value, it is possible to specify which pixels will be counted to define the reference area. With the knowledge of the area of the reference segment from a primary calibration, the area of one pixel can then be calculated.

In a second step, the solar cell under test is measured and all pixels belonging to the cell area are counted by defining an appropriate threshold value. Since the pixel area is known from the previous calibration, the area of the sample under test, or the area of the mask used to define the active solar cell area, can be calculated.

> "Since the measurement of the entire *I–V* curve takes considerably longer than the measurement of I_{sc} alone, the correct thermal conditions must be ensured."

Spectral responsivity measuring procedure

To determine the spectral responsivity of the DUT, the relative DSR is measured between 280 and 1,200nm in 10nm steps at 25°C. To address

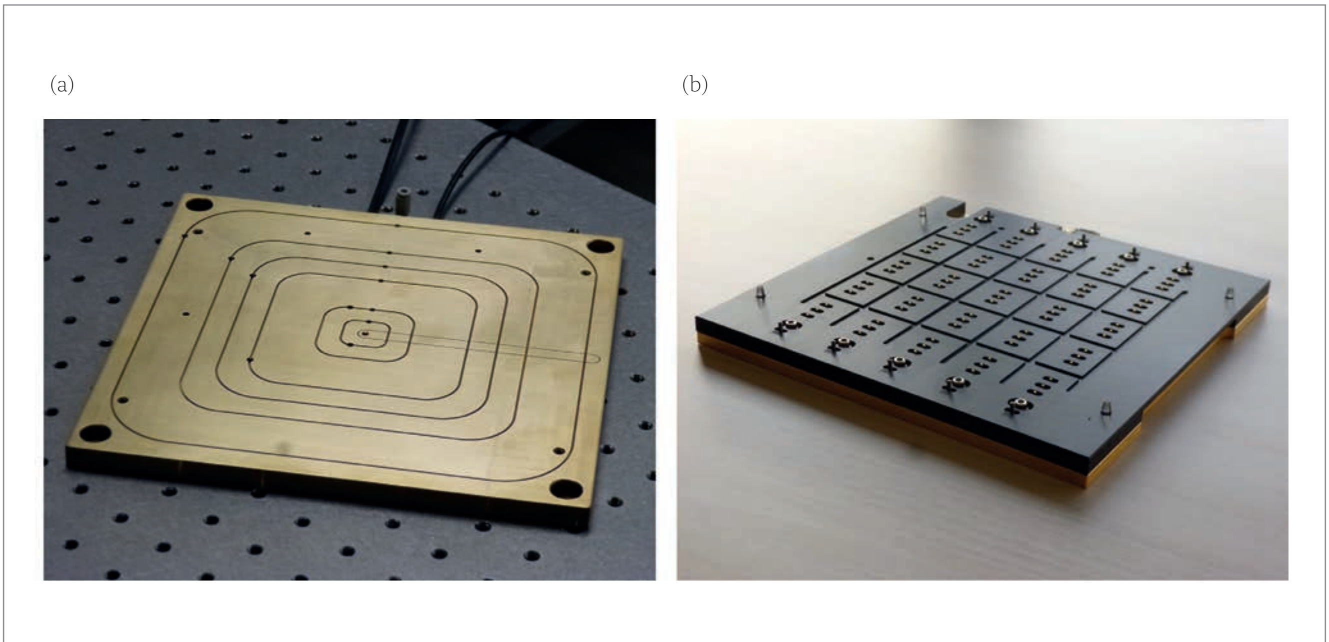

Figure 4. (a) A standard rear-contacting unit with an electrically isolated sensing segment embedded into the contacting plate. (b) A bifacial contacting unit for local rear contacting of solar cells with five busbars.

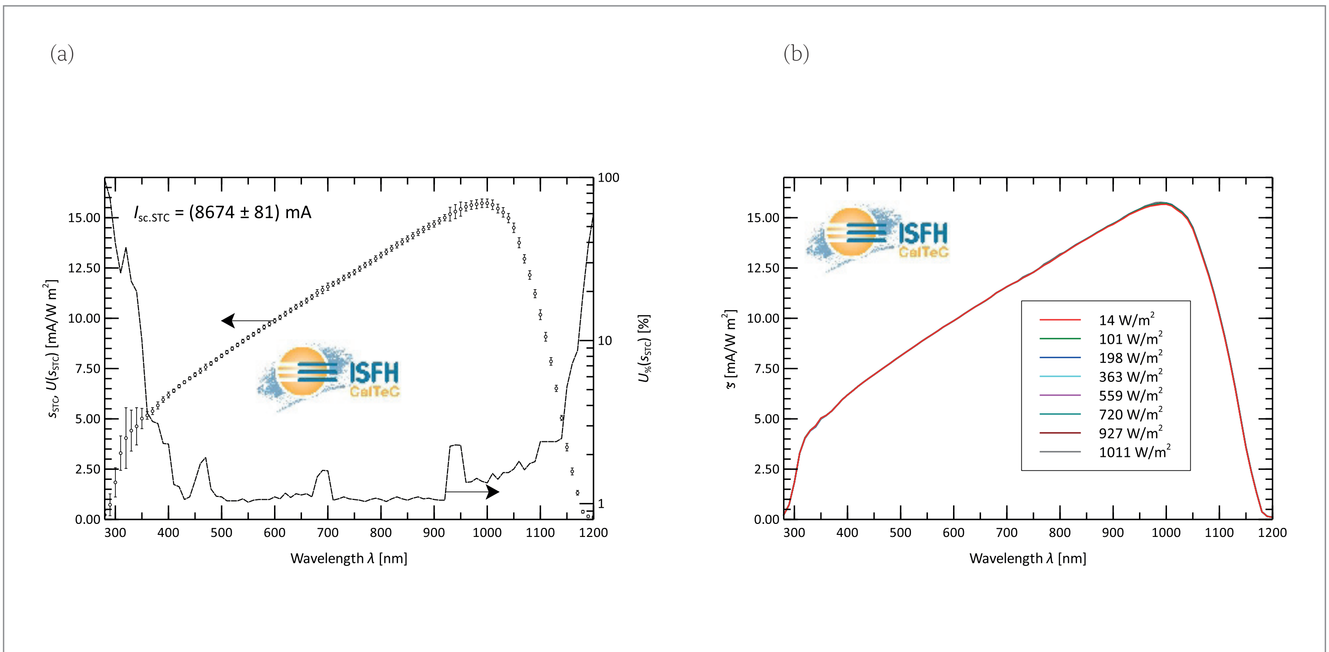

Figure 5. (a) Spectral responsivity curve of a 156×156mm² large-area industrial silicon solar cell; (b) the set of eight DSR curves used for the calculation.

non-linearities, this data acquisition is repeated at more than six bias irradiance levels E ranging from 10 to 1,100W/m^2. If measurements of the solar cell temperature coefficients are requested, an additional set of measurements is performed at 50°C to account for temperature-dependent changes in the spectral mismatch factor MM.

The relative (non-differential) SR is derived mathematically from this DSR data set [17]. The SR curve is used in the subsequent I–V curve measuring procedure to calculate the spectral mismatch correction factor MM [18]. Thus, the correct short-circuit current I_{STC} of the DUT is determined; this I_{STC} value is then used to scale the measured relative DSR and the calculated relative non-differential SR curves to absolute units. A typical final spectral responsivity data set as provided in the calibration document is shown in Fig. 5.

I–V curve measuring procedure

The measurement of the I–V curve is carried out in three steps. The first step consists of determining the shadowing-free short-circuit current of the solar cell without any shading due to a contacting scheme. In the second step, the contacting scheme is implemented for the full I–V curve, and the irradiance of the sun simulator is increased to obtain the same shadowing-free short-circuit current measured in step 1. Finally, in the third step, the entire I–V curve is measured.

The DUT is kept at 25.0°C in darkness, and the I_{sc} measurement is performed directly after opening the high-speed shutter as a function of time. The minor heating of the solar cell during this short period of time can be neglected because of the small temperature coefficient of I_{sc}.

The measurement of I_{sc} requires that there is negligible shading from the contacting unit; this is realized by electrically contacting the cell with Kelvin probes on the outer end of the cell busbars. Since a low busbar conductivity might cause considerable deviation from short-circuit conditions, the voltage on the busbar at the middle of the cell is measured. If this value is above 200mV, a negative voltage is applied to the Kelvin probes until the centre voltage falls below 200mV; the maximum allowed negative bias voltage is 1V. If these requirements cannot be met at the same time, or if the solar cell has an interrupted busbar, a contact bar variation is performed. In this case, I_{sc} is measured as a function of the number of contacting bars, and the shading-free true I_{sc} value is determined by extrapolation to zero busbars.

After I_{sc} has been determined, all contact bars are mounted and the solar simulator irradiance is increased to compensate for the resulting shading. At this stage, the spectral mismatch correction MM is also determined; this factor is always calculated with respect to the actual sun simulator spectrum measured with the integrated spectral radiometer in advance of each calibration.

Since the measurement of the entire I–V curve takes considerably longer than the measurement of I_{sc} alone, the correct thermal conditions must be ensured. The approach taken here is to determine the 25°C-equivalent open-circuit voltage by applying the V_{oc}–t method [9]. For this, the temperature of the solar cell under test is adjusted in darkness to 25°C, measured on the solar cell rear using a PT-1000 temperature sensor. Afterwards, the solar simulator high-speed shutter is opened and the open-circuit voltage is measured as a function of time. The maximum of the resulting curve is the best approximated value for $V_{oc,eq}$ at 25°C under illumination.

For the final measurement of the I–V curve, the shutter of the solar simulator remains open. The temperature of the measurement chuck is adjusted until the continuously measured V_{oc} equals $V_{oc,eq}$. The I–V curve is then measured using a four-quadrant current–voltage source. A defined voltage is applied and the current supplied by the cell is measured as a voltage drop across a calibrated high-power resistor. The current measurement for each data point takes about one second, and the entire I–V curve is measured within one to two minutes, depending on the number of voltage steps used. To check for possible hysteresis effects, two sweeps are performed: the first from V_{oc} to I_{sc}, and the second from I_{sc} to V_{oc}. Finally, the characteristic solar cell parameters are extracted using the procedure published by Luque [19] and Paviet-Salomon [20]. A typical I–V curve together with the characteristic parameters is shown in Fig. 6.

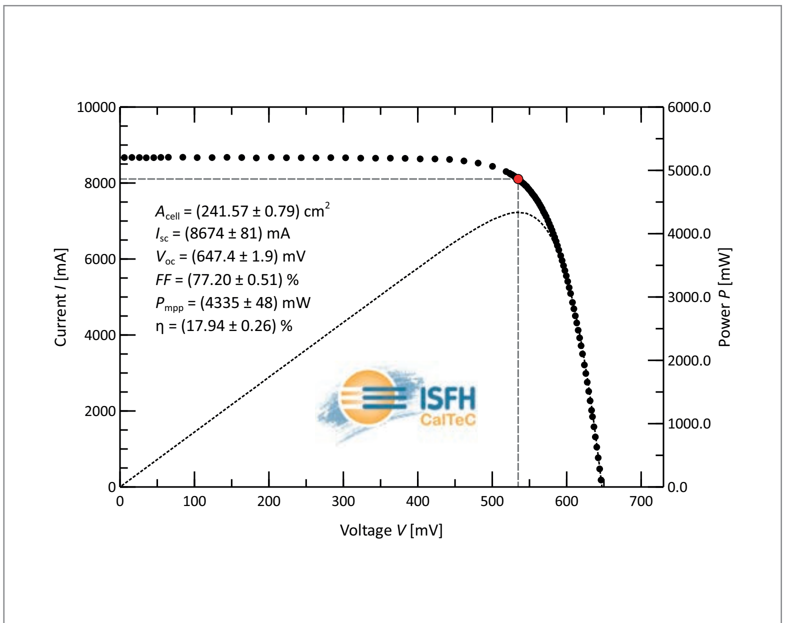

Figure 6. Measured *I–V* curve and calculated characteristic parameters for a 156×156mm² large-area industrial silicon solar cell.

Temperature coefficients

The temperature coefficients α, β and δ, corresponding to I_{sc}, V_{oc} and P_{max} respectively, are determined from the I–V curves measured at 20, 25, 30, 40 and 50°C. For each temperature, the desired characteristic parameters are determined and plotted as a function of temperature. Since the solar simulator spectrum is a good approximation of the AM1.5G reference spectrum [21], the change in the spectral mismatch factor is usually so small that an adjustment of the irradiance is subject to greater uncertainty than a mathematical correction. Instead, each $I_{sc}(T)$ value is multiplied by $C = f_{mm}(T_{STC}) / f_{mm}(T)$, with $f_{mm}(T)$ being the spectral mismatch factor at the temperature T, assuming that a spectral mismatch correction was performed for the 25°C measurement. The V_{oc} and P_{max} values need no further correction. The respective data sets are fitted linearly, and the slopes of the fits divided by the reference temperature T_{STC} of 25°C yield the temperature coefficients; as an example, this is shown for V_{oc} in Fig. 7.

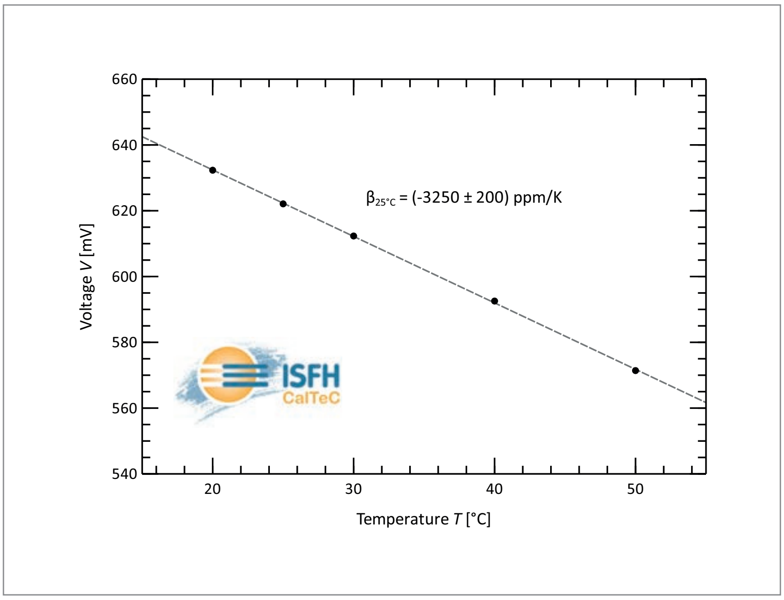

Figure 7. Temperature coefficient β of the open-circuit voltage determined from the slope of a linear fit to a V_{oc}–T data set.

International comparability

Within the framework of the EURAMET ENG55 'PhotoClass' project, financed by the European Metrology Research Programme (EMRP), three intercomparisons were recently carried out between eight international solar cell calibration laboratories. One round robin was organized to document the current uncertainty in the measurement of the short-circuit current temperature coefficient [5], while a second one was performed to document variations in the calibration of reference solar cells [6]. A third intercomparison was carried out to provide information about the status of linearity measurements of short-circuit current versus irradiance [7]. In all three intercomparisons, ISFH CalTeC showed excellent agreement with the other participants, confirming the high measurement accuracy and precision of the ISFH solar cell calibration laboratory. To illustrate this, the results relating to **α**, the short-circuit current temperature coefficient, are shown in Fig. 8.

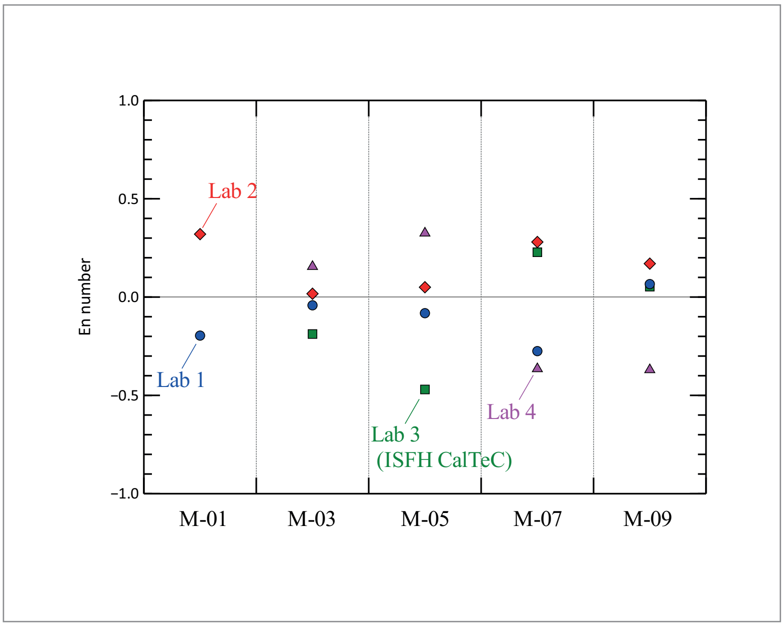

Figure adapted from Salis et al. [5].

Figure 8. E_n numbers of the temperature coefficient α of the short-circuit current for five different reference cells measured by four different calibration laboratories; ISFH CalTeC is Laboratory 3. The E_n value [22,23] is a measure of how good the agreement is of two measured values when taking into account their measurement uncertainties: $E_n = 0$ corresponds to complete agreement, and $|E_n| < 1$ ensures an overlap of the uncertainty ranges and is often taken as the reference condition. The E_n values are calculated with respect to the weighted mean.

Summary

ISFH CalTeC provides solar cell calibration measurements in accordance with the requirements of the IEC 60904 standards for laboratory and industrial solar cells as well as for reference cells in WPVS design. The German accreditation body DAkkS confirms that ISFH CalTeC fulfils the general requirements for the competence of testing and calibration laboratories as defined in the IEC/ISO 17025 standard. ISFH CalTeC offers solar cell calibration as a worldwide service.

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Karsten Bothe studied physics at the Technical University Braunschweig, Germany, the University of Sussex, Brighton, U.K., and the University of Oldenburg, Germany. In 2006 he received his Ph.D. in physics from the University of Hannover, Germany, for his work on oxygen-related trapping and recombination centres in boron-doped crystalline silicon. After an appointment as a research fellow at the Nara Institute of Science and Technology (NAIST), Japan, in 2007, he became head of the solar cell characterization group at ISFH. Since 2016 he has been in charge of the solar cell calibration laboratory at ISFH CalTeC.

David Hinken studied physics at the University of Hannover, Germany, and the University of La Laguna, San Cristóbal de La Laguna, Spain. He received a Diploma degree in physics from the University of Hanover in 2007, followed by a Ph.D. in physics from the same university in 2012, with a thesis topic of luminescence-based characterization of crystalline silicon solar cells. In 2015 he joined the solar cell calibration laboratory of ISFH CalTeC as deputy head, where he is responsible for solar cell calibration equipment, scientific supervision and customer service.

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