Accurate Measurement of New Type Non-silicon Solar Cells’ Photoelectric Conversion Efficiency

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Abstract. Different from traditional silicon solar cells, new type non-silicon solar cells are composed of various kinds of materials, such as organic, perovskite, quantum dots and so on. They always show special performance in spectral responsivity, compatibility and stability, which brought great challenges for the accurate measurement of photoelectric conversion efficiency. We will illustrate a method for accurate efficiency measurement mainly in the view of metrology. Based on effective traceability and calibration of the standard value, a procedure for new type non-silicon solar cells’ efficiency measurement would be proposed. Main influencing factors such as spectral mismatch will also be analysed. Hope to provide a reference method for the accurate characterization of the photoelectric properties of various new types of solar cells.

1. Introduction

New type non-silicon solar cells, such as organic, perovskite, quantum dots solar cells, etc., have become hot spots in science research. They are low cost and flexible, and most importantly their photoelectric conversion efficiency is surging up [1-6]. However, they also have unique properties in spectral responsivity, stability and compatibility, which largely make it a challenging task for accurate measurement of efficiency. Lack of accuracy, reliability and mutual recognition for the efficiency data has seriously influenced solar cell research. Mischaracterized and invalid efficiency results have been reported in a number of journals, improvement of measurement accuracy was urgently needed [7-9]. Nature publishing group have announced a reporting checklist for solar cell manuscripts, which composed of ten items like a questionnaire to be answered.

The measurement inaccuracy is largely due to ineffective traceability of standard value and special properties of new type solar cells [10]. For example, a PTB7-Th/PC71BM-based polymer solar cell, when measured under the same solar simulator, but with two different reference solar cells, KG5 filtered or non-filter reference solar cells, the J-V curves are significantly different as shown in Figure 1. The relative deviation of efficiency is 9.3%, which cannot be ignored [11]. Scientists call for an accurate method of efficiency measurement for new type solar cells.

In this paper, combining the effective traceability of standard value with samples’ own special properties, we presented an accurate method of current-voltage characteristics measurement for new type non-silicon solar cells. Measurement details, calculation of spectral mismatch factors, and main influencing factors were also illustrated. A whole procedure was proposed for accurate measurement.
of new type non-silicon solar cells’ photoelectric conversion efficiency. It can traceable to SI units, and the route is applicable to most of new type solar cells’ efficiency measurement.

Figure 1. The measured J–V results of a PTB7-Th/PC71BM-based polymer solar cell, when use different reference solar cells to calibrate the same solar simulator [11].

2. Measurement

2.1. Traceability
Photoelectric conversion efficiency is defined as the ratio of output power to input power, it can be calculated out according to the solar cell’s I-V characteristics under standard test conditions (STC: 1000W/m², AM1.5G, 25°C) [12]. Practically, I-V characteristics were measured under solar simulators which calibrated to STC state by reference solar cell [13]. As illustrated in Figure 2, reliable calibrated value (CV) and effective traceability to it are critical to efficiency measurement.

Figure 2. Route map of solar cell’s efficiency determination under STC.

The route in Figure 2 is mature for silicon solar cells. While for new type non-silicon solar cells, problems emerged because of spectral responsivity mismatch and other relevant mechanisms. Considering new type non-silicon solar cells’ own properties, we developed a measurement procedure as shown in Figure 3. Firstly, measure the spectral responsivity (SR) or external quantum efficiency (EQE). Secondly, choose calibrated reference solar cell and solar simulator simultaneously according to spectral mismatch factor (MMF) data [14], which is a result of mutual matching and coordination. The reference solar cell should be previously calibrate to obtain its CV (I_sc-STC) by DSR method [15, 16], which is traceable to SI units through standard detectors. Cryogenic radiometer is the highest standard for this traceability chain. International comparisons of standard detectors and reference solar cells were carried out regularly to achieve international mutual recognition. The solar simulator should
be finely adjusted and calibrated according to the requirements of IEC 60904-9, which includes spectral mismatch, non-uniformity and instability of irradiance intensity [17, 18]. During our measurement, a highly matched double-light solar simulator and silicon reference solar cell were chosen because of their excellent MMF data. The practical 1000W/m² irradiance and AM1.5G spectra of STC conditions was calibrated in this step to guarantee the effective value traceability [12, 13]. Finally, whole I-V curves with critical parameters such as short circuit current, open circuit voltage, and maximum power data, would be obtained after scan parameters set by the measurement software. After the effective area calibrated, photoelectric efficiency would be calculated out. The value is traceable to SI unit, so that guarantee the reliability and mutual recognition.

![Schematic map for accurate measurement of new type solar cell’s efficiency.](image)

**Figure 3.** Schematic map for accurate measurement of new type solar cell’s efficiency.

### 2.2. Spectral mismatch factor calculation

Spectral mismatch can be calculated according to equation (1) [14]. If the spectrum of solar simulator \( E_{source}(\lambda) \) is the same as reference spectral irradiance distribution \( E_{ref}(\lambda) \), or the spectral response of the reference solar cell \( s_{ref}(\lambda) \) is the same as the test solar cell \( s_{test}(\lambda) \), MMF=1, no modification is needed.

\[
\text{MMF} = \frac{\int_{\lambda_1}^{\lambda_2} E_{ref}(\lambda) s_{ref}(\lambda) d\lambda \int_{\lambda_1}^{\lambda_2} E_{source}(\lambda) s_{test}(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} E_{ref}(\lambda) s_{test}(\lambda) d\lambda \int_{\lambda_1}^{\lambda_2} E_{source}(\lambda) s_{ref}(\lambda) d\lambda}
\]

(1)

For silicon-based solar cells, no matter mono-Si or poly-Si sample, have similar spectral responsivity. Under single-light or double-light solar simulator, the mismatch errors (MMF-1) are all small enough, as results shown in Table 1. We can consider it as an uncertainty component.

**Table 1.** (MMF-1) calculation results of the mono-Si and poly-Si solar cell measurement, by using the same mono-Si reference solar cells under NIM’s two different solar simulators.

| Sample   | Double-light solar simulator | Single-light solar simulator |
|----------|------------------------------|------------------------------|
| Mono-Si  | -0.06%                       | -0.16%                       |
| Poly- Si | 0.24%                        | -0.59%                       |

While most of new type non-silicon solar cells, such as organic, DSSC and perovskite solar cells, their spectral responsivity are largely different from silicon reference, leading to non-negligible mismatch error. Take perovskite solar cell as a typical example. Figure 4a demonstrated the spectral...
responsivity curves of mono-Si reference solar cell (Black) and the sample (Blue), while Figure 4b corresponding to KG5-filter Si reference solar cell (Black) and the same sample (Blue). We can see neither mono-Si nor KG5-filter Si reference solar cell can well-match to its spectral responsivity. Then the spectral distribution of light source became critical for the total MMF calculation. Figure 4c displayed the spectral irradiance of NIM’s double-light (Black) and single-light (Red) solar simulator compare to AM1.5G standard spectral irradiance (Green). The double-light solar simulator, which composed of Xenon lamp and halogen lamp with a tailor-made filter, its mismatch with AM1.5G or AM0 can be adjusted to smaller than 5% with 50 nm integral, in the range of 300 nm to 1800 nm. The critical tailor-made filter has two sides which play different roles. One side can make the Xenon lamp irradiance above 700 nm be absorbed, while below 700 nm be reflected into the light path. And the other side makes the halogen lamp irradiance below 700 nm be absorbed, while above 700 nm get through into the light path.

![Figure 4](image)

**Figure 4.** a) Spectral responsivity curves of mono-Si reference and a perovskite solar cell; b) Spectral responsivity curves of KG5-filter Si reference and a perovskite solar cell; c) Spectral distribution of double-light and single-light solar simulator compare to AM1.5G standard spectral irradiance.

Here for terrestrial solar cell, it is mean to match with AM1.5G. Table 2 displayed the MMF calculation results of the perovskite solar cell with different references and solar simulators, according to equation (1). Obviously, double-light solar simulator with mono-Si reference solar cell has the smallest spectral mismatch error, only -0.08%. It is the best partner of light source and reference solar cell. If use a mono-Si reference and a single-light solar simulators to measure the perovskite solar cell without modification, a deviation of 10.4% would be induced, so huge that cannot be ignored. Usually, if the mismatch error is smaller than 1%, no irradiance modification is needed, or else, irradiance modification should be conducted. That is, the original irradiance should be divided by the MMF value to obtain the corrected irradiance. Coordination between the light source and reference solar cells determines the MMF value. Table 2 also illustrated that the highly-matched double-light solar simulator is critical to reduce the mismatch error.

| Reference solar cell       | Double-light solar simulator | Single-light solar simulator |
|----------------------------|------------------------------|-----------------------------|
| Mono-Si Ref                | -0.08%                       | -10.4%                      |
| KG5-filtered Si Ref        | 1.0%                         | -1.5%                       |

2.3. *Other influencing factors*

Above is to guarantee the effective traceability of the calibrated value, also to guarantee the first two conditions of STC that is 1000W/m² and AM1.5G. The third condition of STC is temperature of 25°C. Accurately speaking, it should be junction temperature of the measured PV device. Under the irradiation of solar simulator, solar cell’s junction temperature will rapidly rise up inevitably. For the reference solar cell, we use a temperature controller to stable it to (25 ± 1)°C, with an embedded Pt100
sensor to monitor the true state. But new type solar cells are always tiny and have no temperature sensor, its temperature coefficient is also usually unknown, so approximate temperature control would be conducted. If possible, temperature coefficient of new type solar cell should also be known.

Besides, I-V characteristics of new type non-silicon solar cells always influenced by scan speed, direction, etc., [19, 20]. For perovskite solar cells, its hysteresis is very common. In order to answer this problem, we developed software match to Keithly 2400 meter, which scan in both directions as well as measure the stabilized power output. Instability is another well-known performance of new type solar cells. They usually decay during measurement or even preservation, because of irradiance or/and humidity, and other factors. Only few of them are stable for a long time when exposed in air environment. In the present situation, scientists always report the highest results selectively in the literature. We hope the instability problems be solved early.

In the last, designated area of new type solar cells are also important for measurement accuracy. New type solar cells are usually tiny and transparent devices, stray light through non-effective area may add the total irradiance randomly. Masks should be taken into consideration, and its size is also critical for the efficiency measurement and calculation. Results between without mask and with masks whose area larger or smaller than cell itself, is vastly different. About the size-choosing of mask, there is no related formal standard yet. Empirically, take the sample’s non-uniformity into consideration, we would employ a slightly smaller mask, and use the mask’s calibrated area as the effective area for solar cell’s efficiency calculation. The mask should be as thin as possible with regular shape. We have made precisely processed and calibrated mask in square and round shapes, with side length or diameter from 3mm to 10mm, which can cover most of the research cells’ size. Besides measured I-V characteristic parameters, such as short circuit current, open circuit voltage, maximum power, efficiency, and so on, measurement conditions would be all demonstrated in the test report. That is reference solar cell’s CV, scan direction, calibrated area of the mask, etc.

Figure 5a has shown the I-V curves of a perovskite solar cell measured by scanning in forward (red line) and reverse direction (blue line), critical photo-electric parameters can be read out from the curves, and efficiency can be calculated by the parameters, as listed below the curves, red corresponding to forward scan, blue corresponding to reverse scan. During these years, we have calibrated various kinds of new type non-silicon solar cells prepared by research institutes and universities. The highest efficiency record for various kinds of new type non-silicon solar cells were demonstrated in Figure 5b. In this scheme, the highest efficiency values measured in our laboratory during Jan. 2014 and Nov. 2017 are listed. As we can see, the highest efficiency record of organic solar cells is 13.9%. The highest efficiency record of perovskite solar cells is 22.4%. Most of the results have been or will be published in famous journals.

![Figure 5](image_url)

**Figure 5.** a) I-V curves of a perovskite solar cell by forward (Red) and reverse scan (Blue). b) Scheme of the measured highest efficiency record for various kinds of new type solar cells.
3. Conclusion
Based on the metrology traceability chain, we illustrated an accurate measurement method for new type non-silicon solar cells’ photoelectric conversion efficiency. Taking the STC conditions and sample-related properties into consideration, main influencing factors were analyzed to reduce the measurement errors. Miscalculation and low comparability can be relieved or avoided by this method, it will provide strong support for the further research and application of new type solar cells.

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