Solar Cell Performance Measurements Under Artificial Lighting Sources

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***Abstract*—In recent years, there has been a growing interest in measurements of photovoltaic solar cells under ambient artificial lighting such as light emitting diode (LED) or fluorescent light sources. Certain classes of solar cells are considered very good candidates for energy harvesting from mostly visible ambient lighting for the purpose of powering internet-of-things devices. However, measurements of the irradiance of these light sources, a key requirement for characterization of solar cells, has been challenging because there are currently no reference solar cells offered by any metrology laboratory for low light artificial measurements. The current approach of using illuminance meters for measuring the irradiance can result in unacceptable discrepancies between different labs. In this work, we take the first steps in demonstrating that a reference solar cell can indeed be calibrated under a well-defined low-light spectrum and can be used to perform current vs. voltage measurements on any test device under any arbitrary low light spectrum yielding consistent results. This work also highlights the pitfall of using lux meters for measuring light intensity and instead advocates for use of an effective irradiance ratio.**

***Keywords*—Ambient light, indoor light, current vs voltage measurements, energy harvesting, irradiance, photovoltaics**

I. INTRODUCTION

With the growing interest in measurements and characterization of solar cells under artificial or natural low light conditions, better testing methods need to be established to minimize inter-lab discrepancies [1]–[3]. Some classes of solar cells, particularly the inorganic III-V materials such as GaInP and GaAs devices [4], [5], and a variety of organic or hybrid photovoltaic materials [6]–[10] are well-suited for energy harvesting under these lighting conditions. However, the lack of a widely-accepted standard reporting condition (SRC) for indoor PV measurements or lack of calibrated reference cells for low light measurements has forced many researchers to use illuminance meters for measurements of the irradiance and report values in lux (lx = lm/m^2) [6], [11]–[13]. Illuminance measurements in units of lx can lead to widely different outcomes between different laboratories when measuring the same device. Two different light sources with identical illuminance at the measurement plane can have substantially different irradiance output on the solar cell, resulting in different short circuit currents (I_{sc}) and other *I-V* curve parameters.

This work proposes a reference-cell-based method for measuring and characterizing solar cells under various indoor lighting conditions. This method requires selection and use of a reference irradiance spectrum with an absolute scale much like the SRC defined by the two air mass (AM) 1.5 spectra (global and direct). Since lux-based measurements have already become commonplace in the low-light *I-V* measurement community, one can still maintain a connection to them by designing a reference spectrum such that the total illuminance equals 1000 lx. The proposed approach significantly streamlines the process of measuring the *I-V* curves under any light irradiance and will allow for the precise computation of the power conversion efficiency (PCE), a determination that is difficult to achieve with low uncertainty with lux-based measurements.

II. EXPERIMENTAL DETAILS

All measurements were performed inside a dark box with two different white LED light sources projected down onto a stage where both the reference and the test solar cells are placed side by side and under the complete illumination of the LED spotlight. The LEDs are fan-cooled and operated in DC mode with a computer-controlled LED driver. The setup is such that the irradiance level is first set based on the photocurrent measurements from the reference cell and the simultaneous effective irradiance computation. Then an electronic switch opens up the source meter to the test cell so that an *I-V* curve sweep can be performed on it, usually from the I_{sc} to the open circuit voltage, V_{oc}.

The light source spectra were measured using an FEL-calibrated spectroradiometer [14] having an uncertainty of about 0.5 % in the spectral range of interest. The differential spectral responsivity (DSR) method was used to calibrate a silicon reference solar cell under the two reference spectra devised for this work [15], [16]. The linearity of the reference cell under these low irradiance conditions was also investigated [17] and it was determined that this particular reference cell is sufficiently linear (lower than 1 % variation) under irradiance levels probed for this work.

III. METHODOLOGY

In order to calibrate a reference solar cell under an artificial light source, a reference spectrum with an absolute irradiance scale needs to be constructed. We constructed two reference spectra shown in Fig. 1 such that one has a correlated color temperature (CCT) [18] of 3000 K and the other has a CCT of 6000 K. Each spectrum has a total illuminance of 1000 lx (lm/m^2), conditions that are considered fairly typical of bright indoor lighting with a warm white and a cool white chromaticity. In order to construct the reference spectra, first a relative spectral irradiance curve $\hat{E}$ was selected based on measurements of a white LED source and then this curve was

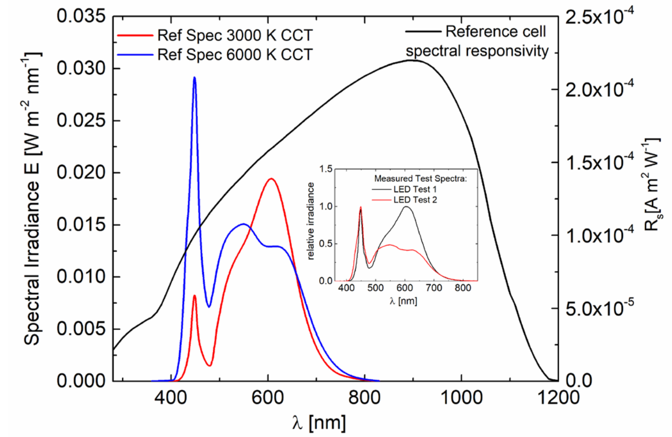

Fig. 1. The two reference spectra constructed for these measurements (left axis). The irradiance spectral responsivity of the reference cell (right axis). Inset shows the spectra of two test lights used for these measurements.

manually modified to have the intended color temperature with a CCT computational worksheet [18]. Then, $\hat{E}$ was multiplied by scalar α so that an absolute spectral irradiance curve $E_r(\lambda) = \alpha\hat{E}(\lambda)$ was computed in units of W.m^{-2}.nm^{-1}:

$$E_v = K_m \int_{360\text{ nm}}^{830\text{ nm}} \alpha\hat{E}(\lambda)V(\lambda)d\lambda\,, \tag{1}$$

where E_v is the illuminance set to 1000 lux, K_m is the spectral luminous efficacy for monochromatic radiation at 555 nm with a value equal to 683 lm/W, and $V(\lambda)$ is the normalized spectral luminous efficiency function, here chosen to be the photopic spectral luminous efficiency function with applications in high light levels such as bright indoor conditions or daylight [19].

In addition to establishing these reference indoor spectra, the spectra of test lights (LED, fluorescent or others) need to be measured, although not in an absolute way. The inset of Fig. 1 shows two test spectra corresponding to two different LEDs that were used as the actual illumination source for the measurements presented here. Within the mathematical framework described below, the spectral profile of the test light does not have to match the reference spectrum. Therefore, a different type of indoor light source such as a fluorescent lamp

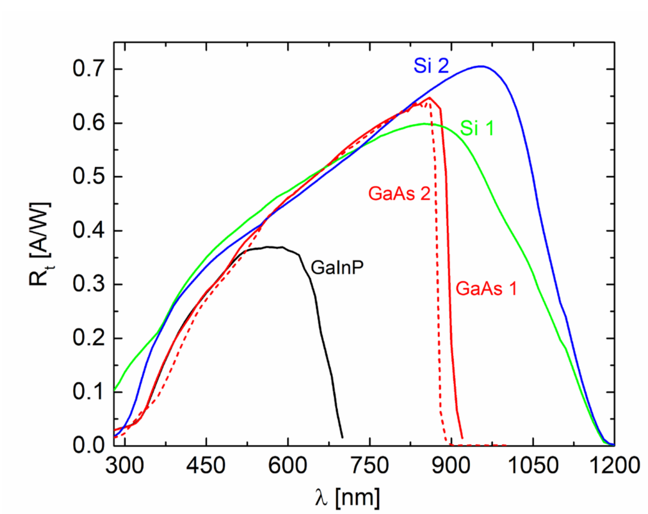

Fig. 2. The spectral responsivity curves of the solar cells tested.

can be used for the *I-V* performance measurements.

The chosen reference cell is a silicon reference cell (nominal area 2 cm × 2 cm) at 25 °C and the DSR method was used to measure its irradiance spectral responsivity, $R_{r,irr}(\lambda)$. Then, the resulting short circuit current, $I_{r,r}$, under the reference spectrum at 25 °C is calculated using [15]:

$$I_{r,r} = \int_{\lambda\,\min}^{\lambda\,\max} E_r(\lambda)R_{r,\mathrm{irr}}(\lambda)d\lambda\,, \tag{2}$$

where the subscript *r,r* stands for reference cell under reference condition. The right axis in Fig. 1 shows the irradiance spectral responsivity curve for the reference cell used in these measurements. The integral computation in (2) gives the following short circuit currents under the two reference spectra, $E_r(\lambda)$: $I_{r,r}^{CCT3k} = 444.98\ \mu\mathrm{A}$, and $I_{r,r}^{CCT6k} = 517.70\ \mu\mathrm{A}$.

A variety of solar cells were selected and characterized for this study. These devices included two types of silicon solar cells, labeled as "Si 1" and "Si 2", one gallium indium phosphide (GaInP) solar cell and two types of gallium arsenide (GaAs) solar cells. Fig. 2 shows the spectral responsivity curves of the 5 test cells in units of A/W. All measurements are based on the DSR technique using a monochromator setup and dc light bias on each cell.

Given a reference spectral irradiance spectrum, a test spectral irradiance (the indoor simulator spectrum) and the spectral responsivities of both the reference and the test solar cells, a spectral mismatch correction parameter, *M*, can be calculated:

$$M = \frac{\int_{\lambda\,\min}^{\lambda\,\max} R_t(\lambda)E_t(\lambda)\mathrm{d}\lambda \int_{\lambda\,\min}^{\lambda\,\max} R_{r,irr}(\lambda)E_r(\lambda)\mathrm{d}\lambda}{\int_{\lambda\,\min}^{\lambda\,\max} R_t(\lambda)E_r(\lambda)\mathrm{d}\lambda \int_{\lambda\,\min}^{\lambda\,\max} R_{r,irr}(\lambda)E_t(\lambda)\mathrm{d}\lambda}\,, \tag{3}$$

where R_t is the spectral responsivity of the test cell, and E_t is the spectral irradiance of the indoor simulator source and can be unscaled. Recalling that the total irradiance incorporates an underlying spectrum to which the PV cells are responsive, one can define a unitless effective irradiance ratio, *F*, given by [20]:

$$F = M\frac{I_{r,t}}{I_{r,r}}\,, \tag{4}$$

where $I_{r,t}$ is the short circuit current of the reference cell under the testing condition, and $I_{r,r}$ is the short circuit current of the reference cell under the reference condition as obtained by (2). The measurement of *F* is readily achieved by monitoring the short circuit current of a calibrated reference cell mounted in the same incident plane of irradiance as the test cell.

With the goal of measuring the performance of these solar cells under the reference condition discussed above, (a) we placed both the reference and the test cells under the illumination source, i.e., indoor solar simulator, (b) calculate *M* for each pair, and (c) adjust the light levels while simultaneously reading $I_{r,t}$ and calculating *F* using (4) so that $F \rightarrow 1$ as best as possible. This may become an iterative process if the spectral shape of the test light changes with sourced current or neutral density filters. In this case, *M* has to be recalculated and *F* remeasured until it is sufficiently close to unity. Once satisfied, a 4-probe *I-V* curve is initiated on the test cell from 0 V to the open circuit voltage, V_{oc}, or in reverse if there are concerns about *I-V* curve hysteresis. The *I-V* curve

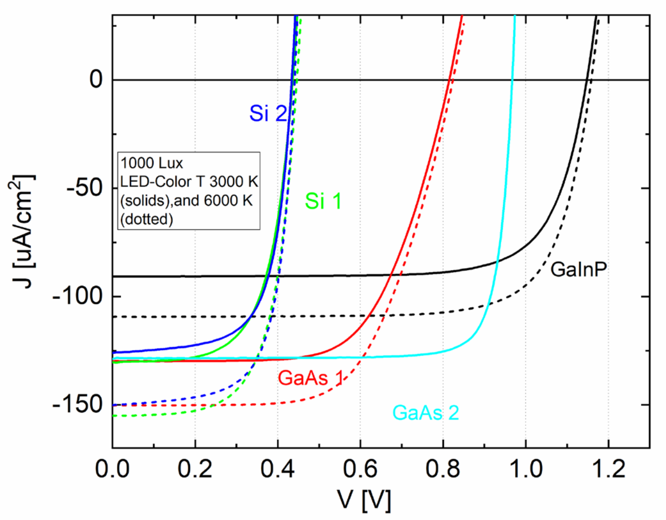

Fig. 3. J-V curves of five different solar cells under two constructed reference spectra, one with a CCT of 3000 K and the other with a CCT of 6000 K.

reported under the reference condition is given by:

$$I_{t,r}(V) = \frac{1}{M}\frac{I_{r,r}}{I_{r,t}} I_{t,t}(V) = \frac{S}{F} I_{t,t}(V), \qquad (5)$$

where S is a uniformity factor defined as the ratio $I_{r,\text{ref cell pos}} / I_{r,\text{test cell pos}}$ for cases of nonuniform light sources.

Fig 3 shows the *J-V* curves for each of the 5 test solar cells described above under the established 3000 K CCT (solid curves) and the 6000 K CCT reference spectra (dotted curves), where J is the current density (=current divided by nominal cell area). For the GaAs2 cell, data was not available under the 6000 K CCT at the time of this submission. These measurements demonstrate that setting up the irradiance with a simple illuminance meter can lead to significant inconsistencies across different types of light sources and the shape of the spectrum plays a non-negligible role. For each of the test cells, it can be seen that the CCT 6000 K reference spectrum produces a higher magnitude J_{sc} and a slightly higher V_{oc} than the 3000 K CCT condition as a result of having a slightly larger total irradiance (≈ 3.7 W/m^2 vs 2.9 W/m^2, respectively).

When the test spectrum has a shape close to that of the reference spectrum, $M \approx 1$ for most of the devices. However, when the test spectrum is cool white with a CCT of 6240 K but the intended reference condition has a CCT of 3000 K, then even silicon test cells show a mismatch parameter as high as 1.025. In general, the computations of all the measurement parameters show that if a spectral correction parameter is not computed for the measurement, then the potential errors are only minimized if either the indoor simulator's spectrum is chosen to be as close to the reference spectrum as possible, or the test and the reference cells are matched. If an inter-lab comparison is being performed when a lux meter is the only available instrument for measurements of light intensity, the two labs should perform the measurements under spectra with similar color temperatures.

Interestingly, under the CCT 6000 K spectrum, the PCE is actually reduced for all cases. The GaInP cell shows a PCE of 26.8 % under the 3000 K spectrum but shows a reduced PCE of 25.9 % under the 6000 K spectrum. Likewise, the GaAs1 cell shows a reduction in PCE from 22.8 % under 3000 K CCT to 20.6 % under 6000 K CCT. This finding is in spite of the fact that the electrical performance parameters, including the maximum power point, P_m, are actually higher under the 6000 K spectrum than under the 3000 K spectrum. The higher CCT spectra pack more of their optical power in the 400 nm to 500 nm regime but the solar cells have lower spectral responsivities (or external quantum efficiencies) in that regime and are unable to tap into this extra power efficiently; therefore, they show a reduction in PCE.

From among the cells tested here, the GaAs2 device truly outperforms the other cells, including the GaAs1 cell by a significant margin. This cell (by Alta Devices [21], [22]) shows a PCE of ≈ 35 % under the 3000 K CCT reference spectrum. Compared to the GaAs1 cell, the GaAs2 cell enjoys a higher V_{oc} and a larger fill factor (83 % vs 65 %, respectively), directly leading to the higher efficiency observed here. One important factor contributing to the GaAs2 cell's outstanding performance appears to be related to a high external luminescent yield, pushing the V_{oc} up closer to its theoretical limit [23], [24].

IV. Conclusion

We outlined a reference cell-based method for performing low-irradiance *I-V* curve measurements on PV devices under indoor ambient lighting. The reference solar cell was calibrated under a carefully chosen reference irradiance and was used to set an effective irradiance ratio during the measurement. Our results confirm a foregone conclusion in the research community that the spectral composition of the light source does indeed affect the performance of the solar cells. Our methodology and measurement approach clearly explain why this dependence exists and lead the way for developing standards to address these measurement challenges.

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