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Variation of the sample temperature due to white bias light irradiation during the spectral responsivity measurement of solar cells and its effect on the measurement result

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A B S T R A C T

The temperature variation of solar cells due to white bias light irradiation during the spectral responsivity measurement and its effect on the spectral responsivity measurement result were investigated for various types of solar cells, such as crystalline silicon (c-Si), Cu(In,Ga)Se_2 (CIGS), and dye-sensitized solar cells (DSSCs). For the investigation, a spectral responsivity measurement system, which can employ the well-known sample temperature control methods (such as the "temperature controlled sample stage" method and the "forced air cooling" method) has been used. Hence, the availability of these sample temperature control methods has also been tested. Through the investigation, it was found that the actual temperature of the solar cells located under the AM1.5G-approximated white bias light can be increased significantly during the spectral responsivity measurement, depending on the sample temperature control methods applied. In addition, it was also found that the increase of sample temperature can lead to a significant error in the measured spectral responsivity, depending on the types of solar cells being measured. In addition, a simple analytic model based on the classical heat transfer theory was developed to understand the temperature variation of the solar cells under the spectral responsivity measurement environment.

1. Introduction

The spectral responsivity of a solar cell is a characteristic measure of a solar cell and is defined as the "output current generated by a solar cell per incident optical power of each wavelength of incident light". The spectral responsivity has been widely used for solar cell development and analysis for a long time [1] because it provides information regarding light absorption, carrier recombination and other processes occurring inside a solar cell. Spectral responsivity is measured by irradiating a solar cell through a narrow-bandwidth (namely, "monochromatic") light source at a series of different wavelengths covering the response range of the solar cell and measuring the short-circuit current of the solar cell and the incident monochromatic light beam power (or sometimes, irradiance) at each of these wavelengths. An AM1.5G-approximated white bias light is typically used to measure the spectral responsivity of the solar cells under standard test conditions (STC) [2].

The accuracy of the spectral responsivity measurement can be affected by various uncertainty components [3]: 1) the calibration uncertainty of the reference device for measuring the optical power (or irradiance) of the monochromatic measurement light, 2) the optical alignment of the reference device and the solar cell under test, 3) the quality of the monochromatic measurement light and the bias light, and 4) other measurement environmental factors (such as, cell temperature variation during the measurement). The uncertainty contributions of these components to the final measurement result can be estimated according to the guidelines in

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Refs. [4], and for some of the uncertainty components, the uncertainty contributions have been carefully studied by several groups [5,6].

In the case of the component "cell temperature variation during the spectral responsivity measurement", most of the previous studies (concerning the spectral responsivity measurement itself or the reference solar cell calibration technique using the spectral responsivity measurement) have reported the situation where the cell temperature is controlled within 25 ± 1 °C during the spectral responsivity measurements [7–10]. However, these studies used quite rigorous sample temperature control methods for reducing their measurement or calibration uncertainties, and in the case of a common solar cell development laboratory, the cell temperature condition (25 ± 1 °C during the spectral responsivity measurement) cannot be easily achieved even if a well-known sample temperature control method is used (details regarding this issue will be discussed later in this paper).

In this study, for the cases where various sample temperature control methods are applied, the actual temperature variation of several solar cells due to the white bias light irradiation during the spectral responsivity measurement were gauged, and the effects of this temperature variation on the measurement result were investigated. For the investigation, along with experimental approaches, a simple analytic model based on the classical heat transfer theory was developed to explain the actual temperature variation of the solar cells under the spectral responsivity measurement environment.

2. Experimental setup

Three different types of solar cells were used for the investigation. The first type was Czochralski silicon wafer-based p-type mono crystalline silicon (c-Si) solar cells manufactured with a process sequence of wafer texturing, doping with phosphorous, anti-reflection coating with silicon nitride (SiN_x), and electrode formation for the front and rear sides [11]. The second type was $Cu(In,Ga)Se_2$ (CIGS) solar cells manufactured with a process sequence of molybdenum (Mo) back electrode formation on a soda-lime glass, growth of the CIGS absorber via the well-known 3-stage process, deposition of cadmium sulfide (CdS) buffer layer, deposition of aluminum-doped zinc oxide (ZnO:Al) window layer, and formation of front electrode [12]. The third type was dye-sensitized solar cells (DSSCs) manufactured with a process sequence of front and rear side electrode formation on two different glass plates, TiO_2 coating on the rear side electrode, absorption of dye on the TiO_2 layer, overlapping the front side electrode on top of the dye absorbed TiO_2 layer, ionic electrolyte injection into the overlapped area, and sealing of the edge of the overlapped area [13]. The c-Si solar cells were manufactured initially with a size of 15.6×15.6 cm^2 and were subsequently cut into smaller cells that had a 1×1 cm^2 dimension for experimental convenience. The CIGS cells were fabricated on $2.5 \times 2.5 \times 0.1$ (thickness) cm^3 glass substrates and scribed into 0.9×0.6 cm^2 cells. The DSSCs were fabricated using $2 \times 2.5 \times 0.22$ (thickness) cm^3 glass plates and had an active (i.e., the dye absorbed TiO_2 layer) area of 0.5×0.5 cm^2.

The spectral responsivity measurements for the solar cell samples were performed using an SOMA Optics Inc., model S-9230 spectral responsivity measurement system, based on the AC-mode measurement method [3], which measures the time-varying short-circuit current of the solar cell samples generated by a chopped monochromatic light under the white bias light irradiation. The spectral responsivity measurement system consists of several components: a measurement light source, a monochromator to convert the measurement light into a narrow-bandwidth (monochromatic) light, a monitoring detector to monitor the instability of the monochromatic measurement light power, a reference detector measuring the optical power (or irradiance) of the monochromatic measurement light, a chopper to convert the continuous monochromatic measurement light into a time-varying (chopped) light during the spectral responsivity measurement, an AM1.5G-approximated white bias light source, a lock-in-amplifier measuring the time-varying photocurrent generated by the solar cell samples, a sample stage providing two different sample temperature control methods, a data acquisition PC, and other optical components (such as a mirror, lens, beam splitter etc.), as shown in Fig. 1. The irradiation areas of both the monochromatic measurement light and the white bias light were approximately 3.2×3.2 cm^2 identically, and the spectral match of the white bias light with respect to the AM1.5G reference spectrum was class B [14]. The effective irradiance of the white bias light was 100 mW/cm^2 (measured using a calibrated reference solar cell), and the chopping frequency for the monochromatic measurement light was 30 Hz. In addition, in the case of the DSSC measurement, a black shading mask, which shades the entire front surface of the samples except the active area, was used to prevent unwanted light absorption through the glass covers.

Note here that, when measuring the solar cells that had a relatively long response time scale (such as DSSCs, perovskite solar cells, etc.), typically, a chopping frequency below 5 Hz is recommended [15,16]. However, in this study, as mentioned above, the chopping frequency of 30 Hz was used for the measurement of DSSCs as well as the c-Si and CIGS cases. This is to apply the same white bias light, the same optical measurement quality, and the same sample temperature control methods to all of the three types of solar cell samples by using only one spectral responsivity measurement system (i.e., the model S-9230; this model provides only chopping frequencies in the range of 30–100 Hz). In addition, although the measurement of the DSSCs was performed using the chopping frequency of 30 Hz, it is sufficient to observe the "relative" variation of the measurement result depending on the cell temperature variation during the spectral responsivity measurement (due to the white bias light irradiation). A similar variation trend of the measurement results due to the sample temperature variation during the spectral responsivity measurement was also observed when the DSSCs are measured using another spectral responsivity measurement systems which provide the chopping frequency below 5 Hz (data are not shown here).

To control the sample temperature during the spectral responsivity measurement, two different methods were used, as shown in Fig. 1-(b). The first was a "temperature controlled sample stage" method, which uses a Peltier-thermostat system. The second one was a "forced air cooling" method, which uses a compressed air injection system. The "temperature controlled sample stage" consists of a brass-made sample mounting plate having the size of $12 \times 12 \times 1.5$ (thickness) cm^3, the Peltier-thermostat system is attached just below the sample mounting plate, and a temperature sensor is embedded inside the sample mounting plate to monitor the temperature of the plate. The sample mounting plate has a periodic array of air suction holes on its surface. The ends of these air suction holes were connected to a small vacuum pump ("rotary-type suction pump" in Fig. 1-(b)) and provided a weak force for attaching for the solar cell samples to the sample mounting plate during the spectral responsivity measurement. The "forced air cooling" system consists of an air compressor to make compressed air, a flexible rubber tube to transport the compressed air, and an air nozzle to blow the compressed air to the solar cell samples. The inside pressure of the air compressor was approximately 1.5 bar, and the inner diameter of the air nozzle was 1.5 mm. The air nozzle was mounted near the edge of the sample stage using a mounting jig and the compressed air was blown onto the solar cell samples.