Solar Energy Materials & Solar Cells 159 (2017) 427–434

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

journal homepage: www.elsevier.com/locate/solmat

Illumination intensity and spectrum-dependent performance of thin-film silicon single and multijunction solar cells

S.N. Agbo*, T. Merdzhanova, U. Rau, O. Astakhov

IEK 5-Photovoltaics, Forschungszentrum Jülich GmbH, d-52425 Jülich, Germany

ARTICLE INFO

Keywords:
Thin-film silicon
Multijunction solar cells
Illumination sources and intensity
Fill factor
Open-circuit voltage
Short-circuit current density

ABSTRACT

The performance of a solar cell is inherently dependent on the illumination spectrum and intensity. Therefore standard characterization under AM1.5 illumination represents only one point in a large parameter space. In view of potential applications in portable electronics, obtaining reference data on the performance under varying light sources and illumination intensity for a comprehensive set of thin-film silicon solar cells (TFSC) is a primary motivation of our study. In addition, illumination dependencies of photovoltaic parameters provide deeper understanding of the operation and limitations of thin-film silicon solar cell for both indoor and outdoor applications. In this paper we assess the performance of single and multijunction TFSC with amorphous (a-Si:H) and microcrystalline (μc-Si:H) absorber layers under common light sources like light emitting diode (LED), halogen, fluorescent and solar simulator with AM1.5 spectrum. The illumination intensity of these light sources has been varied over several orders of magnitude (0.01–230 mW/cm^2) to explore a wide range of operating conditions for the solar cells. We observed expected increase in efficiency with increase of the illumination intensity (up to approximately 1 sun) of all cells and naturally strong dependence on the illumination spectrum. For example, the efficiency reached impressive 20% for a-Si:H cells under LED illumination while it is below 4% under halogen bulb. More detailed analysis performed in this work shows that the cell parameters are not always following diode model predictions mostly due to the bias-dependent collection in drift driven thin-film silicon solar cells. The results first of all provide reference for the assessment of energy gain from TFSC in various illumination conditions. It also provides better view into the limitations of TFSC and potentials for improvement especially for the non-standard illumination spectra and intensities.

1. Introduction

Thin-film silicon solar cell (TFSC) technology has an attractive option of flexible adjustment of output voltage by means of monolithic stacking of cells with amorphous silicon (a-Si:H) and microcrystalline silicon (μc-Si:H) absorber layers in a multijunction solar cell [1,2]. The voltage range reported up to date starts from approximately 0.5 V and reaches 2.8 V for 4-junction solar cell devices [3]. This option opens new applications for TFSCs where it can be directly coupled to the electrochemical energy storage, e.g. H_2 production by means of water splitting [2,3]. One other direct way of coupling the solar cell to energy storage is to connect it to a rechargeable battery. High voltages reached by multijunction TFSC are of interest here as well. For application in integrated photovoltaic PV/battery set-ups, multijunction solar cells delivering voltage of up to 3 V can be used directly to charge storage batteries [4]. For practical purposes, it is important that these multijunction solar cells are able to charge storage batteries at illumination conditions different from the standard AM1.5 under which the cells are usually characterized. The current-voltage I(V) characterization of photovoltaic devices at the standard AM1.5 illumination providing reliable results to compare cell performance however does not reflect the real operation condition of solar cells either for indoor or outdoor applications [5,6]. Collecting reference data for the evaluation of potential energy outcome of thin-film silicon solar cells in various illumination conditions under commonly available artificial light sources is the first motivation for our study. Characterizing solar cells at illuminations other than AM1.5 have been reported for various solar cell types: crystalline silicon [7–10], thin-film silicon [11–14] and also for organic solar cells [15]. The published data however is not sufficient to estimate potential outcome of different state-of-the-art single junction and multijunction solar cells under popular artificial light sources. In addition, studying the behavior of solar cells under different illuminations gives a clearer understanding of the cells' operation when compared with the standard illumination characterization [12]. This experimental investigation is even more critical for indoor characterization under artificial lighting since there is still no international

* Corresponding author.
E-mail address: s.agbo@fz-juelich.de (S.N. Agbo).

http://dx.doi.org/10.1016/j.solmat.2016.09.039
Received 22 July 2016; Received in revised form 23 September 2016; Accepted 26 September 2016
Available online 07 October 2016

standard for making such indoor characterization [16].

In this report, we present a systematic study on the illumination intensity dependencies of I(V)-characteristics measured with illumination from halogen bulb, fluorescent bulb, light emitting diode (LED) and solar simulator for single junction and multijunction TFSCs based on a-Si:H and μc-Si:H absorber layers. The experimental characteristics of the solar cells are analyzed and correlated to the most basic theoretical predictions.

2. Experimental details

2.1. Solar cells deposition

The solar cells were deposited using radio frequency plasma-enhanced chemical vapor deposition (rf-PEVCD) using up-to-date optimized deposition conditions. The single junction a-Si:H and μc-Si:H solar cells were deposited in superstrate configuration on Corning glass with ZnO:Al as front contact and ZnO:Al/Ag/ZnO:Al as back contact/reflector. The thicknesses of the absorber layers in the single junction cells were respectively 300 and 1000 nm. The tandem and triple-junction cells were deposited on SnO_2:F coated glass type Asahi-VU. The tandem cells have superstrate configuration with a top a-Si:H p-i-n, n-type μc-Si:H as the tunnel recombination junction (TRJ) and a bottom μc-Si:H p-i-n [17]. The triple-junction cells also have the superstrate configuration with the structure composed of a-Si:H/μc-Si:H/μc-Si:H (hereafter refered to as Triple A) and a-Si:H/a-Si:H/μc-Si:H (hereafter refered to as Triple B) absorber layers. The detailed deposition conditions and the characterization procedure for the multijunction cells as carried out in our group are presented elsewhere [18,19].

The cells were characterized by a current-voltage measurement under the spectrum and illumination intensities of LED, halogen, fluorescent and reference AM1.5 spectrum. The temperature of the measurement platform was maintained at 25 °C for all the measurements, nonetheless the heating effect of high intensity illumination on the solar cells was not accounted for though considered negligible. The PV parameters of all the test cells measured under standard AM1.5 illumination are presented in Table 1.

2.2. Light sources and spectra

Commercially available and widely spread artificial lighting bulbs were used in this study. They consist of a white LED (EC 1194/2012 from OSRAM), halogen lamp (H488 from Lightway), and fluorescent tube (4 W/25 from Radium NL). The standard AM1.5 illumination from Wacom class A solar simulator at 25 °C was used as a reference for comparison. The illumination spectra of the light sources presented in Fig. 1 were measured using a spectrophotometer. The illumination intensities were varied using neutral density filters and Fresnel lens placed between the light source and the solar cell; perpendicular to the illumination and about 10 cm from the sample.

Table 1
The PV parameters of the test solar cells measured under standard AM1.5 illumination.

Solar cell	PV parameters			
	J_{sc} [mA/cm^2]	FF [%]	V_{oc} [V]	η [%]
a-Si:H	16.0	67.3	0.94	10.1
μc-Si:H	24.4	68.7	0.51	8.5
Tandem	12.1	74.4	1.35	12.2
Triple A	8.1	73.2	1.85	11.1
Triple B	5.5	78.7	2.22	9.6

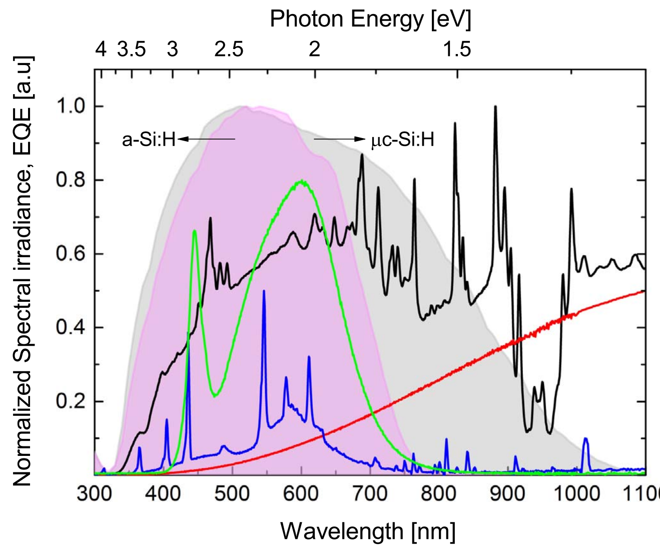

Fig. 1. Normalized spectral irradiance of the different light sources used for this study in comparison with the normalized external quantum efficiency (*EQE*) of thin-film a-Si:H and μc-Si:H solar cells. The sun simulator spectrum (black line) is AM1.5 illumination obtained from Wacom class A solar simulator. The red, blue and green lines represent halogen, fluorescent and LED spectrum respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2.3. Estimation of illumination power and cell efficiency

The efficiency η of a solar cell is determined by the output electric power of a solar cell divided by the illumination power according to the relation

$$\eta = \frac{FF \times J_{sc} \times V_{oc}}{P_{in}} \tag{1}$$

where FF, J_{sc}, V_{oc}, and P_{in} are the fill factor, short-circuit current density, open-circuit voltage and the input illumination power respectively. The quantity P_{in} is obtained usually by integrating the measured spectral irradiance with respect to the wavelength. For standard characterization of solar cell under AM1.5 spectrum, the input illumination power is 100 mW/cm^2. For non-standard illumination conditions such as illumination under the light sources above, it is critical to determine the P_{in} to be able to obtain the cell efficiency. In contrast to highly homogeneous illumination intensity provided by solar simulator over the sample area (10×10 cm^2 substrate with several 1×1 cm^2 solar cells) the illumination from point-like artificial light sources is not homogeneous over the substrate area. To minimize measurements of the spectral irradiance and simplify the procedure, we measured the spectral irradiance for the position of one cell and used the J_{sc} of the cell at the same position to determine the ratio J_{sc}/P_{in} for each light source. Using this ratio the input power is obtained for all cells on the substrate using J_{sc}.

3. Theoretical considerations

It is instructive to get an overview of the expected effect of the varied illumination intensity on the photovoltaic parameters of a solar cell. The I(V) characteristics of solar cells can be described using the basic diode equations and the equivalent circuits [12,20]. The circuit consists mainly of a current source and a diode in the one-diode model which assumes that the shunt resistance goes to infinity and the series resistance is zero as in ideal solar cell [20]. This model however was mainly implemented to describe the electrical behavior of p-n crystalline silicon solar cells but has also been used in p-i-n thin-film solar cells [12,21–24]. In TFSC with device-grade absorber layer, recombination is ignored and hence the standard one-diode model is used to describe the cell operation especially at standard AM1.5 illumination