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Analysis of the light-induced degradation of differently matched tandem solar cells with and without an intermediate reflector using the Power Matching Method

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ABSTRACT

We investigate the light-induced degradation of a-Si:H/μc-Si:H tandem solar cells by applying the Power-Matching-Method (PMM). The PMM allows for a characterization of a cell under various matching conditions by systematically varying the spectral distribution of the illumination. The top cell's thickness was varied from 100 nm to 500 nm for cells with and without SiO_x intermediate reflector layer (IRL). The method provides a powerful means of comparing the degradation of differently matched tandem cells. We conclude that the IRL does not significantly affect the stability of our sub cells. The method reveals that only the top-cell degrades significantly under illumination. In addition, the study shows that the PMM is useful for outdoor performance estimations of tandem solar cells or modules.

1. Introduction

The sub-cells of thin-film tandem solar cells are connected in series and, therefore, the currents of the sub-cells are equal at all operating conditions. In order to minimize the losses resulting from the series connection, the sub-cells' thicknesses are commonly adjusted [1]. This adjustment is referred to as the matching of a solar cell. Tandem cells for which the short-circuit current of the top cell is lower (or higher) under standard test conditions is referred to as a top-limited (or bottom-limited) cell. If the currents of the sub-cells are equal in short circuit current, the cell is (short-circuit) current-matched. The current matching is most commonly realized to optimize efficiency. However, as has been shown before [2,3], the short-circuit current-matching does not lead to the optimum output power if the current/voltage (*JV*)-characteristics of the top and bottom cell differ. In this article, the aspect of an optimum matching will be discussed in the context of light-induced degradation [4].

Besides the losses resulting from the current limitation, the series connection of tandem cells inherits additional challenges in the characterization of such devices [5,6]. A major challenge is that the *JV*-characteristics of the sub-cells are experimentally not accessible. Furthermore, the experimentally accessible *JV*-characteristic of the overall tandem cell strongly depends on the matching of the cell [7–10]. Therefore, the measured *JV*-characteristic is misleading. For a proper interpretation, the matching of the device needs to be taken into account. Differences in the solar cell parameters may result from differences in sub-cell properties and differences in matching. As a consequence, it is difficult to adequately compare differently matched tandem solar cells [8]. The comparison of the light-induced degradation of tandem cells is even more challenging, because the matching of the device changes during degradation time, as the sub-cells do not show the same degradation behavior [11].

In this work, we present a powerful method to compare the light-induced degradation of differently matched tandem solar cells. We discuss this method exemplarily for the degradation of a-Si:H/μc-Si:H tandem cells. The applied method examines the device under illumination conditions with different spectral distributions and has first been introduced to optimize the matching of tandem cells [12]. Because the blue light is mainly absorbed in the top cell (band gap energy $E_g \approx 1.7$ eV [13]) and the infrared light from the bottom cell ($E_g \approx 1.2$ eV [14]), this spectral variation leads to different matching conditions. Therefore, the tandem cell

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is characterized under different matching conditions and, hence, is comparable to differently matched cells.

In the following we extend this so-called Power-Matching-Method to more detail as well as testing it for specifically interesting experiments. We apply the method at different light soaking times and discuss the matching-dependent degradation of tandem devices. Finally we introduce an approach, which allows for a matching-independent comparison of the degradation of tandem cells. We verify this approach experimentally and with the help of device simulations. In the end we present one more very feasible application of the Power-Matching-Method, i.e. the use for outdoor yield predictions of tandem devices.

2. Experimental details

2.1. Solar cell preparation

A plasma enhanced chemical vapor deposition (PECVD) system using an excitation frequency of 13.56 MHz was used for deposition of a-Si:H/μc-Si:H tandem solar cells [15] on SnO_2:F coated glass from Asahi type VU. For the back contact, sputtered ZnO:Al/Ag back reflectors were applied. A laser-patterning defines the exact cell area of 1 cm^2.

The thicknesses of the top-cells vary from approximately 150 nm to 500 nm, whereas the bottom cells thickness is kept constant at about 1.8 μm. The integration of an intermediate reflector layer (IRL) made of μc-SiO_x:H alloys between the sub-cells allows effective current transfer from the bottom to the top cell [16,17]. Consequently, the difference in the short-circuit current densities of the top and the bottom cell ΔJ_{SC} covers the range from -3.9 mA/cm^2 to 4 mA/cm^2 in our experiments.

2.2. Degradation setup

The experiment examines the light induced degradation of several a-Si:H/μc-Si:H tandem solar cells. The devices under test are characterized by the Power-Matching-Method at different light soaking times t_{LS}=0, 3, 20, 84, 172, 308, 620 and 1000 h. The sun simulator used for degradation, illuminates the device under test homogeneously (non-uniformity less than 1.5%) and the samples were placed on a temperature controlled sample holder at 50 ± 2°C.

3. Power Matching Method

In order to understand the main idea of the Power-Matching-Method it is crucial to understand the dependence of the *JV*-characteristic of the tandem device on the spectrum of the irradiance. The key lies in the relation between the experimentally accessible *JV*-characteristic of the tandem cell and the non-accessible *JV*-characteristics of the sub-cells it is composed of, as well as their dependence on the spectral irradiance.

3.1. Superposition of sub-cells JV-characteristics

Fig. 1 visualizes *JV*-characteristics of the sub-cells for different spectra and the resulting *JV*-characteristic of the tandem device. The *JV*-characteristics of the sub-cells have been simulated with the Advanced Semiconductor Analysis Software (University of Technology Delft), which is commonly used for silicon thin-film solar cell modeling [18–21], for three spectra that differ in the spectral distribution but not in the overall intensity. The variation of the spectral distribution leads to different matching conditions. For a spectrum with a high fraction of infrared light, which is

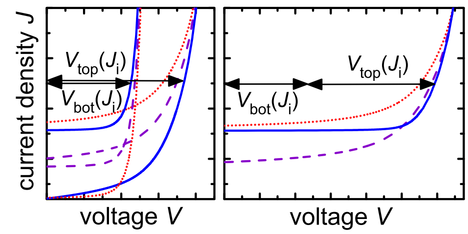

Fig. 1. (a) Simulated current density/voltage(*JV*)-characteristics of a top and bottom cell for different spectra with the same intensity, varied from high red fractions (top-limitation, dotted – red) over a balanced spectrum (dashed – violet) to high blue fractions (bottom-limitation, solid-blue). (b) The resulting *JV*-characteristic of the tandem cell is strongly matching dependent and varies in short-circuit current, efficiency and fill-factor.

mainly absorbed in the bottom cell, the short-circuit current of the top cell is lower than that of the bottom cell (top-limitation, dotted red). The cell is still slightly top-limited under the standard AM1.5g spectrum (dashed violet). However, when adding intensity in the blue spectral range, mainly absorbed by the top cell, the short-circuit current of the top cell exceeds that one of the bottom cell. Under this irradiance the tandem cell is strongly bottom-limited (solid blue). The simulated sub-cells' *JV*-characteristics can then be combined to simulate the *JV*-characteristic of the overall tandem device. Note at this point, that only the overall *JV*-characteristic of the tandem device (Fig. 1b) is experimentally accessible, but not the characteristics of the sub-cells.

Since the tandem cell is connected in series, the current of the top and the bottom cell is always equal whereas its respective voltages add up to the overall voltage of the tandem cell, $V(J_i) = V_{top}(J_i) + V_{bot}(J_i)$. Fig. 1b shows the calculated *JV*-characteristic of the tandem device for the three different spectra. All three *JV*-characteristics differ in fill factor, short-circuit current and efficiency. The AM1.5g spectrum for example leads to a higher short-circuit current, the fill-factor is however higher under bottom-limitation. This dependence of the solar parameters on the matching of a tandem cell makes the comparison of tandem solar cells very challenging.

The Power-Matching-Method characterizes the same tandem cell under various matching conditions by varying the spectral distribution of the irradiation. The aim is to gain additional information about the tandem device. The method enables a more adequate comparison of tandem devices than the characterization under one standardized spectrum could provide.

3.2. Power Matching Setup

We used a dual source class A sun simulator from WACOM (tungsten and xenon lamps) with additional high power LED bias-light sources for the spectral *JV*-characterization. The samples were fixed to a temperature controlled sample holder at 25 ± 0.2 °C.

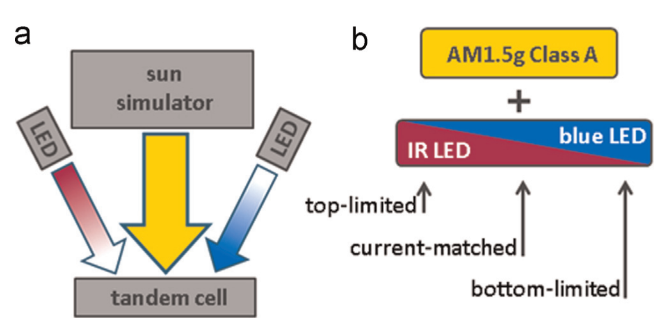

Fig. 2. (a) Experimental setup of the Power-Matching-Method. (b) Infrared and blue LED light is added to the AM1.5g class A sun simulator spectrum in a way that the same tandem cell can be measured under various matching conditions.