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Optimized short-circuit current mismatch in multi-junction solar cells

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ABSTRACT

Multi-junction photovoltaic devices include two or more component sub-cells which are electrically interconnected in series. At any power point, the current output of the total device is limited by the sub-cell with the smallest current density. Therefore, the maximum efficiency is reached when the sub-cells have equal current densities at their respective maximum power points. In this case the sub-cells are so called “power matched”. We report an experimental procedure in which the current–voltage characteristics of tandem solar cells can be measured under various irradiance spectra, i.e. under various short-circuit current matching conditions. This permits the probing of the optimized short circuit current mismatch, where the sub-cells are power matched, which is essential to define design rules for the tandem stack. The method applies well to devices where one of the sub-cells is metastable. We show that, in the case of thin-film silicon tandem cells, the optimum mismatch changes significantly after light induced degradation. Consequently, the degradation factor of such devices is shown to depend not only on material quality but also on the initial short circuit current matching. This experiment also provides relative quantification of the fill factors of each sub-cell. Our example suggests that a high bottom cell deposition rate can be detrimental to the fill factor of the top cell in the case of thin-film silicon tandem cells deposited in superstrate configuration.

1. Introduction

Stacking solar cells with materials of different band gaps reduces thermalization losses and therefore increases the efficiency limit of a photovoltaic device [1]. In such multi-junction configurations, the sub-cells can be electrically connected in series. This implies that, at a given power point, the sub-cell with the smallest current density will limit the current density of the whole device. To maximize the power conversion efficiency, the sub-cells should have equal current densities at their respective maximum power point (MPP), this current density being then the MPP current density of the multi-junction device [2]. This so-called “power matching” condition [3] differs from the short-circuit current (J_{SC}) matching condition, unless the current–voltage (I–V) characteristics of the sub-cells are identical [4]. In thin film multi-junction devices, one sub-cell can exhibit meta-stability effects, which makes the device optimization for stabilized-state operation more difficult.

In the case of micromorph tandem cells, a high band gap (1.6–1.8 eV) hydrogenated amorphous silicon (a-Si:H) top cell is combined with a low band gap (1.1 eV) microcrystalline silicon (μc-Si:H) bottom cell. Because of the top cell light induced degradation (LID) known as the Staebler–Wronski effect [5], this sub-cell usually has a lower fill factor than the bottom cell after stabilization. Consequently, in this configuration simulations [6] have shown that the current of the total device should be slightly limited by the bottom cell, in short circuit condition, to reach power matching and thus maximize the efficiency. It should be noted that this optimization should be made according to the irradiance spectrum.

The balance of photocurrent between the sub-cells can be tuned by changing the thickness of the a-Si:H and μc-Si:H layers or, more advantageously, by using intermediate reflectors based on zinc oxide (ZnO) [7] or silicon oxide (SiO_x) [8]. The J_{SC} of each sub-cell is easily obtained by the measurement of separated external quantum efficiencies (EQE) [9]. J_{SC} matching is therefore straightforward to evaluate. However, probing the power matching requires either the complete I–V curve of the sub-cells [10], or the measurement of the total device efficiency under different irradiance spectra while keeping the same total current in the tandem device [3].

In this paper, we use a method similar to [3] in order to determine the optimal J_{SC} mismatch of micromorph devices with different top and bottom cell performances, before and after LID, i.e. after 1000 h of light soaking under 1 Sun. After introducing the “current matching” apparatus and the calculations involved, we

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present a sample series where we have varied the electrical quality of both sub-cells by using different substrate roughnesses and bottom-cell material qualities, obtained through varying the deposition rate. Then, the *I–V* parameters of the sample series are plotted as a function of the short-circuit current matching of the sub-cells. Finally, we discuss the impact of these series parameters on the performance of each sub-cell and its effect on the optimized J_{SC} mismatch. Our experimental data is supported with simulated results obtained from an equivalent network model.

2. Experiment

2.1. Current matching set-up

Illuminated *I–V* measurements are performed under a class AAA Wacom solar simulator (WXS-220S-L2 AM1.5G) following the Standard Test Conditions (STC). The irradiance spectrum is therefore close to AM 1.5G with an irradiance intensity of 1000 W/m^2 (1 Sun). To study micromorph devices in the degraded state, light soaking for 1000 h is done using a Solaronix system with an irradiance intensity of 1 Sun.

In this experiment, *I–V* curves of micromorph tandem cells are measured under an intentionally modified irradiance spectrum, in order to artificially change the current matching condition of the tandem device. The sum of the J_{SC} of the sub-cells (hereon referred to as “total current”) is kept constant; only the ratio of the top and the bottom sub-cell J_{SC} varies. Consequently, the number of incident photon is kept constant but not the irradiance power density. Therefore, we will consider in the following the power output of the devices and not their efficiency.

We refer to the set-up that enables us to modify the spectrum as the “current matching machine” (CMM). The CMM set-up is illustrated in Fig. 1: the intensity of the AM 1.5 STC spectrum irradiance is reduced by 15% thanks to the reflection of two tilted glass slides. The attenuation is homogenous between 370 and 1100 nm. To compensate for this irradiance reduction, the light intensity corresponding to 15% of the total current of the tandem device is added and redistributed to the top and the bottom cells with two dedicated light sources. The balance of current distribution between the top and the bottom sub-cell can be tuned by adjusting the power of each selective light source. In the case of micromorph devices, we use monochromatic LEDs emitting at 470 and 870 nm for excitation of the top and bottom cells respectively. This experiment could be applied to other types of multi-junction devices by adapting the selective light biases.

The LED's electronic power is controlled by in-house electronics and a National Instruments USB-6009 acquisition card. The LEDs optical power is calibrated using a Hamamatsu photodiode with known EQE. The relative emission spectra of the LEDs are measured with an Arcoptics spectrometer. The EQE of the sub-cells is measured with an apparatus similar to that described in [8].

The electronic power needed from the blue LEDs to obtain the desired top-cell current is given by

$$Pwr_{B_{LED}}(J_{scT}) = \frac{\int[(QE_{top}(\lambda)/QE_{ref}(\lambda))B_{spec}(\lambda)]}{B_{spec}(\lambda)} Pwr_{B_{LED}}(J_{sc\ ph}), \qquad (1)$$

where $Pwr_{B_{LED}}$ is the optical power of the blue LEDs, J_{scT} is the short-circuit current in the top cell, λ is the wavelength, B_{spec} is the spectrum of the blue LEDs, $J_{sc\ ph}$ is the J_{SC} of the reference Hamamatsu photodiode, QE_{top} and QE_{ref} are the quantum efficiencies of the top cell and reference photodiode respectively.

The same calculation applies for the red LEDs and the bottom cell. According to these calculations, a sub-cell-specific calibration is made. First, one sub-cell is saturated by increasing its J_{SC} by 5 mA/cm^2, so that the other subcell limits the current; then, the J_{SC} of the limiting sub-cell is increased by steps of 0.5 mA/cm^2. Consequently, the J_{SC} of the total device should increase at each step by 0.5 mA/cm^2. The mean of actual J_{SC} increase in the total device is used to correct the calculated electronic power in the LED needed to obtain the desired current in each sub-cell.

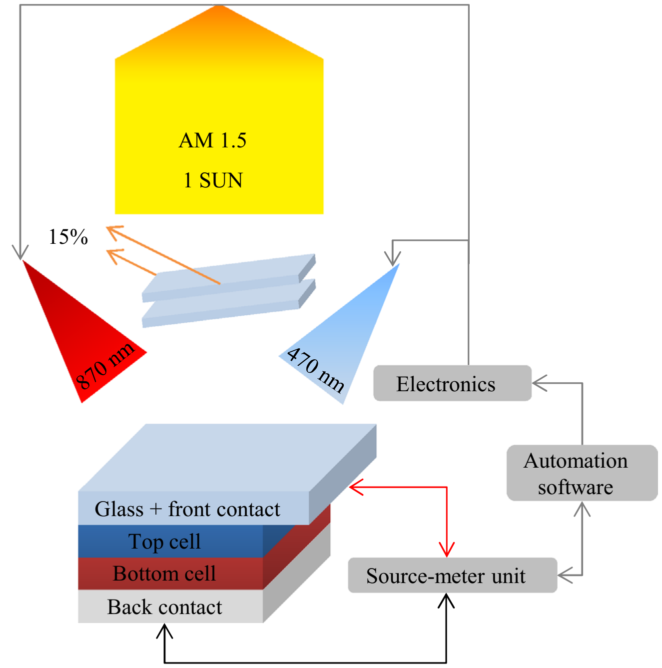

Fig. 1. Sketch of the current-matching-machine experimental set-up. It aims at measuring *I–V* curves under various irradiance spectra. 15% of the intensity of the STC AM 1.5G spectrum irradiance is removed thanks to two glass slides. The decrease in total current is compensated with monochromatic LEDs in order to keep the total current constant. The blue (470 nm) and red (870 nm) LEDs permit tuning of the photocurrent of the top and bottom cells respectively.

2.2. Measurement procedure

After these sub-cell-specific calibrations, we define an array of J_{SC} matching conditions for illuminated *I–V* measurements (typically 8 points). J_{SC} matching conditions are here on referred to as J_M and given by

$$J_M = (J_{EQE\_top} - J_{EQE\_bot}) + (J_{ad\_top} - J_{ad\_bot}), \qquad (2)$$

where J_{EQE_top} and J_{EQE_bot} are respectively the J_{SC} of the top and bottom cells calculated from EQE measurement and J_{ad_top} and J_{ad_bot} are respectively the photocurrent added in the top and the bottom cell thanks to the two selective LEDs sets.

The chosen J_M are restrained by the fact that only 15% of the total current can be redistributed. We calculate, for each J_M, the corresponding additional photocurrent needed for the top and bottom sub-cells, and according to formula (1), the corresponding blue and red LED power required. The power required is then corrected using the sub-cell-specific calibration. After performing *I–V* measurements under the different spectral conditions, we get plots of each tandem cell *I–V* parameters with respect to J_M. The maximum J_{SC} of the tandem device is obtained at short circuit current matching of the sub-cells ($J_M = 0$ mA/cm^2). The maximum power output is reached at power matching. The calibration and *I–V* measurement steps are fully automated and performed in less than 5 min for one device under test.