SEPARATION OF THE I-V CURVE OF EACH COMPONENT CELL OF MULTI-JUNCTION SOLAR CELLS

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ABSTRACT

Characterization of the performance of multi-junction devices (solar cells and modules), such as the a-Si/thin-film c-Si structure, includes more technological complexity than that of single-junction devices. It is useful to understand the effect of the spectrum and irradiance of the incident light on the performance of the multi-junction devices, in order to estimate their performance under various climate conditions. Characteristics of multi-junction devices depend on the photocurrent generated by the component cells and their I-V curves. Therefore, information on the I-V curve of each component cell is important to characterize the devices precisely. In this study, a method to separate the I-V curve of each component cell of the monolithic multi-junction devices is successfully developed.

INTRODUCTION

Multi-junction devices (solar cells and modules), such as the a-Si/thin-film c-Si structure, have been attracting attention to increase the conversion efficiency of photovoltaic devices. For example, in the case of amorphous silicon solar cells, the multi-junction structure helps to minimize degradation effects, leading to higher “end of life” efficiency [1] [2]. Characterization of the performance of multi-junction devices includes more technological complexity than that of single-junction devices. It is useful to understand the effect of the spectrum and irradiance of the incident light on the performance of the multi-junction devices to estimate their performance under various climate conditions. However, their effect is more complex than that of the single junction devices, because component cells with different properties are series-connected in a device. The characteristics of multi-junction devices, such as the short circuit current (I_{sc}), open circuit voltage (V_{oc}), maximum power (P_{max}), and fill factor (FF) depend on the photocurrent generated by the component cells and their I-V curves. Therefore, information on the I-V curve of each component cell is important to characterize the devices precisely. However, evaluation of the I-V curve of each component cell of the multi-junction devices is not straightforward because the component cells are usually monolithically integrated on a substructure. So far, several approaches to separate the component I-V curves were reported [1] [3] [4] [5]. However, those methods require theoretical I-V formula or parameter fitting, and are not directly applicable to various kinds of multi-junction devices, especially when theoretical I-V formula are not well known. In this study, a method to separate the I-V curve of each component cell of the monolithic multi-junction devices using the experimental I-V curves measured under different spectral conditions is successfully developed. Dependence of the I-V curve on the spectral irradiance, which is important for translating the I-V curve into that under other conditions, is also investigated.

EXPERIMENTAL PROCEDURE

Basic flowchart

The present method is based on the experimental I-V curves measured at four different spectral conditions, and does not require theoretical I-V formula or parameter fitting. An example of the basic procedure for a tandem device is shown in Fig. 1. Details of the steps in the Figure (A)-(F) are described below.

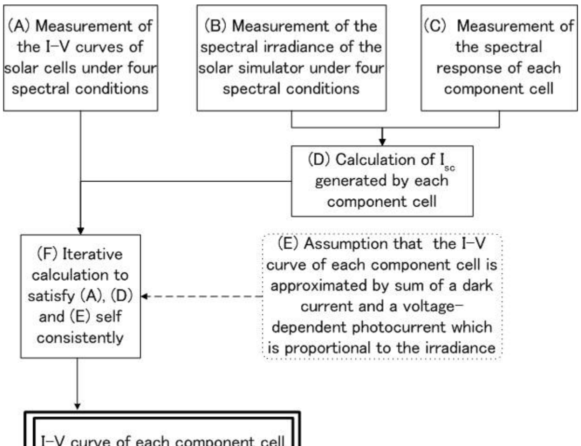


Fig.1 Example of the basic procedure for the separation of the I-V curve of each component cell of the double junction solar cells.

Measurement of I-V curve (A)

Four I-V curves ($I_n(V)$:n=1, 2, 3, 4) of the device at four spectral conditions by using filtered solar simulator light were measured (Fig. 2). An a-Si / thin-film crystalline Si tandem solar cell was used as the sample. The cell temperature was kept at 25 °C.

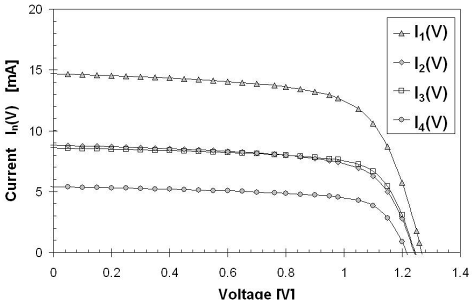


Fig.2 Measured I-V curves of the device at four different spectral conditions using filtered solar simulator light.

Measurement of spectral irradiance (B)

The spectral irradiance of the filtered solar simulator light ($E_n(\lambda)$, n=1, 2, 3, 4) was measured (Fig. 3).

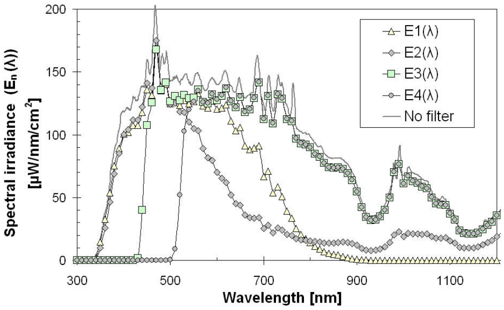


Fig. 3 Measured spectral irradiance of the solar simulator light and filtered solar simulator light.

Measurement of spectral response (C)

The spectral response of the component cells ($S_{top}(\lambda)$, $S_{abot}(\lambda)$) was measured (Fig 3). Appropriate color bias light was irradiated in order to obtain the spectral response of each component cell [8].

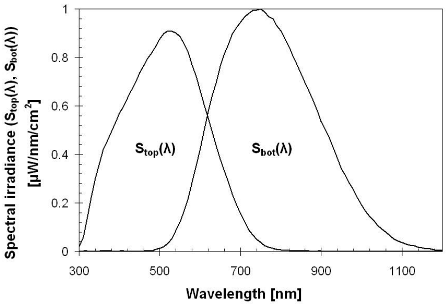


Fig.4 Relative spectral response of the top and bottom cells.

Calculation of relative short circuit current of each component cell (D)

Relative short circuit current of each component cell under four spectral conditions ($C_{n,top}$, $C_{n,bot}$), which are normalized to the values at the standard test conditions (STC: AM1.5 global, 100 mW/cm^2, 25 °C), was calculated from the spectral irradiance of the filtered solar simulator light ($E_n(\lambda)$) and the spectral response of the component cells ($S_{top}(\lambda)$, $S_{bot}(\lambda)$) by using equations (1) and (2).

$$C_{n,top} = \frac{\int S_{top}(\lambda)E_n(\lambda)d\lambda}{\int S_{top}(\lambda)E_{STC}(\lambda)d\lambda} \tag{1}$$

$$C_{n,bot} = \frac{\int S_{bot}(\lambda)E_n(\lambda)d\lambda}{\int S_{bot}(\lambda)E_{STC}(\lambda)d\lambda} \tag{2}$$

Here,

$E_{STC}(\lambda)$: The spectral irradiance of AM1.5global standard sunlight.

Fig. 5 shows the plots of the $C_{n,top}$ and $C_{n,bot}$. The spectrum is “blue-rich” when $C_{n,top}>C_{n,bot}$ and “red- rich” when $C_{n,top}<C_{n,bot}$. When $C_{n,top}=1$ and $C_{n,bot}=1$, the spectrum is AM 1.5G standard sunlight.

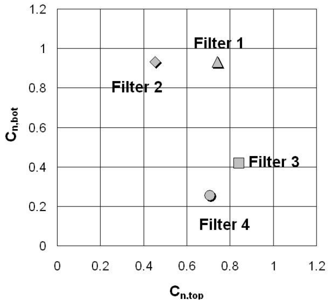


Fig.5 Calculated relative short circuit current generated by each component cell.

Iterative calculation (E) and (F)

Equations (3)-(5) are assumed for the separation of the I-V curves. The I-V curve of each component cell is expressed by the sum of a dark current and a voltage-dependent photocurrent, which is proportional to the short circuit current (equations (3) and (4)). This is known to be valid for various kinds of solar cells including c-Si, a-Si and thin-film crystalline silicon solar cells, etc [6] [7].

$$I_{n,\,top}(V)=I_{d,\,top}(V)+C_{n,\,top}\cdot I_{ph,\,top}(V) \tag{3}$$

$$I_{n,\,bot}(V)=I_{d,\,bot}(V)+C_{n,\,bot}\cdot I_{ph,\,bot}(V) \tag{4}$$

The output voltage of multi-junction solar cells is the sum of each component cell (equation (5)) [8].

$$\mathbf{V_n(I)=V_{n,\,top}(I)+V_{n,\,bot}(I)} \qquad (5)$$

Here,

$V_{n,\,top}(I)$, $V_{n,\,bot}(I)$ and $V_n(I)$ is the inverse function of $I_{n,top}(V)$, $I_{n,\,bot}(V)$ and $I_n(V)$, respectively.

The dark current ($I_{d,\,top}(V)$ and $I_{d,\,bot}(V)$) and photocurrent ($I_{ph,\,top}(V)$ and $I_{ph,\,bot}(V)$) of the component cells under the experimental conditions ($E_n(\lambda)$) were calculated by iterative calculations to satisfy the results of (A), (D), (E). Then the I-V curves of each component cell under STC and dark conditions ($I_{STC,\,top}(V)$, $I_{d,top}(V)$, $I_{STC,\,bot}(V)$, $I_{d,\,bot}(V)$) were calculated by using equations (3) and (4) as the result (Fig. 6).

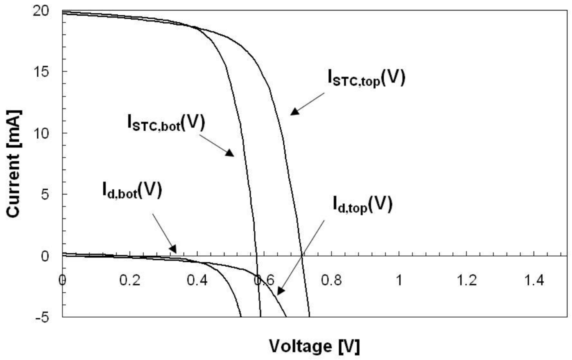


Fig.6 Separated I-V curves ($I_{d,\,top}(V)$, $I_{d,\,bot}(V)$, $I_{ph,\,top}(V)$ and $I_{ph,\,bot}(V)$).

COMPARISON OF THE CALCULATION WITH THE EXPERIMENT

The I-V curves under various irradiance and spectral conditions can be calculated by using separated I-V curves of each component cell ($I_{stc,\,top}(V)$, $I_{dark,top}(V)$, $I_{stc,\,bot}(V)$). The calculated I-V curves are compared with the measured I-V curves (Fig.7). Fig. 8 shows the relative short circuit current generated by each component cells. The calculated I-V curves of the multi-junction device well agree with the experiment as shown in Fig. 7. This result has confirmed that the I-V curve of each component cell is successfully separated by the present method (equations (1)-(5)). Recently, it has been reported that the irradiance dependence of the multi-junction devices can be expressed by simpler formula under limited conditions [6]. The present study offers a method to estimate the I-V curves of the multi-junction devices under wide variety of irradiance and spectral conditions.

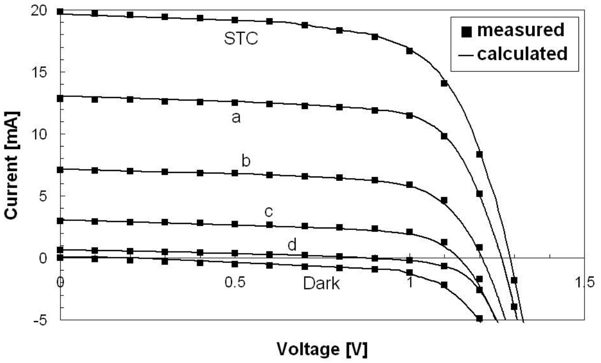


Fig.7 Measured (square) and calculated (lines) I-V curves of the devices under several spectral and irradiance conditions.

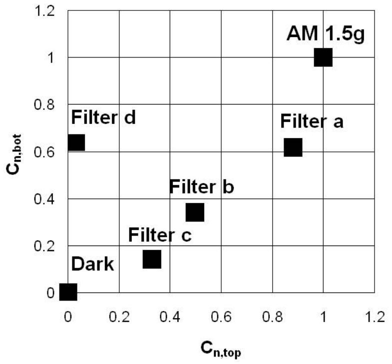
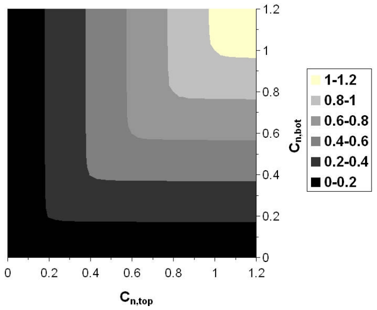


Fig.8 Calculated relative short circuit current generated by each component cell under several spectral and irradiance conditions (shown in Fig. 7).

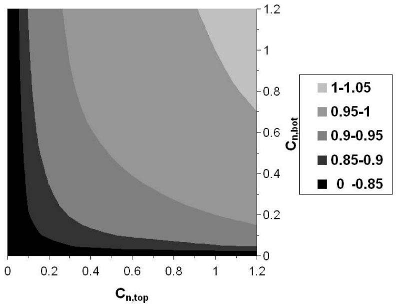
SIMULATION OF I-V CURVE PARAMETERS

Figures 9 (a)-(d) show results of I_{sc}, V_{oc}, P_{max} and FF under very wide range of $C_{n,top}$ and $C_{n,bot}$ such as 0 (dark)-1.2 (1.2 times of STC), which are calculated by using equations (3)-(5) based on the separate I-V curves of the component cells (shown in Fig. 6). The I-V curve parameters are normalized to the values under STC. The variation of I_{sc} is rather simple, and is limited by the component cell with smaller I_{sc}. However, the variation of FF is more complex because it is affected by the shape of both component cells. These results indicate that the translation of the I-V curves for irradiance is not straightforward, especially when the balance of the component cell varies.

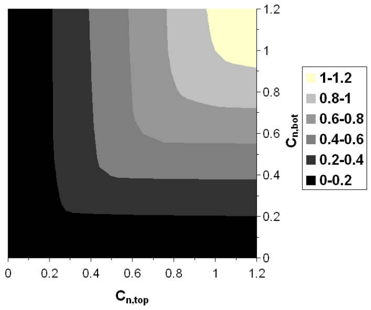
It is noted that, although the ambiguity in the series resistance and V_{oc} of each component cell remains in the present procedure, the total V_{oc} and the series resistance of the multi-junction device are correctly reproduced.



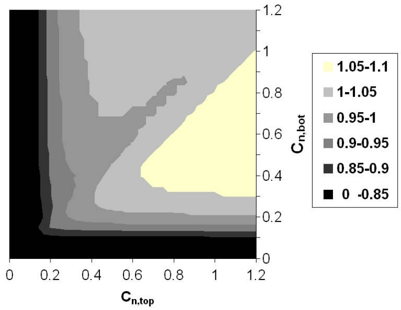
(a) I_{sc}



(b) V_{oc}



(c) P_{max}



(d) FF

Fig. 9 Contour plot of the calculated (a) I_{sc}, (b) V_{oc}, (c) P_{max} and (d) FF of the devise, plotted versus the relative short circuit current of the top and bottom cells.

CONCLUSIONS

In this study, a method to separate the I-V curve of each component cell of the monolithic multi-junction devices using the experimental I-V curves measured under different spectral conditions has been discussed. It has been confirmed that the I-V curve of each component cell is successfully separated by the present method, which is basically applicable to any kinds of multi-junction devices regardless of the structure and material.

I-V curves and parameters such as I_{sc}, V_{oc}, P_{max} and FF under various spectral and irradiance conditions can be calculated by using the present method.

ACKNOWLEDGEMENTS

This work was supported in part by NEDO under the Ministry of Economy, Trade and Industry.

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