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Effect of spectral response of solar cells on the module output when individual cells are shaded

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ABSTRACT

Solar cell characterization is carried out by current-voltage (I-V) and spectral response measurements. These characteristics of the solar cell depend on solar cell design, fabrication, material properties, junction depth and optical coatings. Generally, during module manufacturing, solar cells of similar wattage are used and spectral response (SR) including external quantum efficiency (EQE) and internal quantum efficiency (IQE) characteristics are not given any attention. It is observed that similar wattage rating crystalline solar cells have slight variation in their spectral response behavior over the wavelength range (300–1100 nm). In this paper, the effect of shading on the crystalline solar cells of the module having same power output and slight difference in spectral response are experimentally investigated. The maximum and minimum drop in short circuit current of the module is observed to be 84.2% and 34.6% when the solar cells of high and low spectral response are shaded. Minority carrier diffusion length and dead layer thickness parameters of solar cells are also calculated from the short and long wavelength region of the spectral response curve. It is found that the effect on module output is high in case of shading a cell having maximum diffusion length and minimum dead layer length. It is concluded that spectral response of a solar cell is an additional parameter that must be considered apart from cell I-V characteristics in module fabrication for superior and uniform performance in the field.

1. Introduction

Photovoltaic (PV) module power output primarily depends on the performance of solar cells used in the module fabrication. The characterization of solar cells is done by I-V characteristics and the conversion efficiency depends on the photo-generated current which is strongly related with quantum efficiency. The quantum efficiency corresponds to the spectral response which determines the spectral distribution effect on the short-circuit current (Yang et al., 2008). The spectral response curve depicts the crystalline solar cell output relative to constant energy input at different wavelengths range from approximately 300–1200 nm (Luque and Hegedus, 2011).

Experimental investigations on the effect of spatial variation of incident radiation on the spectral response of solar cells and modules have been carried out by different researchers. Rüther et al. (2002) monitored and compared the outdoor operation of amorphous silicon (a-Si) solar modules with that of crystalline silicon (c-Si) technology and concluded that a-Si are more efficient in winter contrast to c-Si solar cells which perform better during summer. Okullo et al. (2011) and Ghitas (2012) investigated the quantitative effects of the solar spectral variations on the performance of multi-crystalline silicon photovoltaic modules and concluded that visible region contribute maximum towards short circuit current compared to infrared or ultraviolet region. Lombez et al. (2014) carried out a micrometric investigation of EQE on microcrystalline $CuInGa(S,Se)_2$ solar cells and observed different spatial fluctuation ranges. Micrometric variations are also observed which are attributed to intrinsic properties of the poly-crystalline absorbers whereas longer range fluctuations are linked to the fabrication process of the microcell. Fernández et al. (2014) studied the spectral variations on the performance of high concentrator photovoltaic modules operating under different real climatic conditions and found that the annual spectral losses vary from 6% to 51% depending on the location and the module. As a non-destructive technique, IQE has also become an important solar cell

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characterization technique. Lan and Green (2015) analyzed the IQE in three different spectral regions resulting in measurement of cell properties like front surface properties, contribution of dark saturation current density, photo carrier collection, etc. due to the different response analysis. The IQE responses of the cells are observed to be slightly varying at the shorter wavelength region whereas in the longer region a larger difference is observed. Dirnberger et al. (2015) studied the impact of varying spectral irradiance on the performance of different PV technologies, which exhibited spectral gains and losses depending on the band gap of the different technologies thus affecting the overall performance.

Spectral response curve also provides the information about two other important parameters namely minority carrier diffusion length (*also measured in terms of minority carrier lifetime*) and dead layer thickness of the solar cells. The minority carrier diffusion length provides the information about the quality of silicon solar cell (Pla et al., 2000; Zhu et al., 2005) and generally larger values of diffusion length implies higher efficiency (Rothemund et al., 2011). On the other hand, the front surface of the solar cell is heavily doped to minimize the contact resistance losses with the metal contact which in turn causes a considerable loss of excess minority carriers in the front region of a diffused junction silicon solar cell. Thus a dead layer is formed where some of the excess minority carriers recombine at the front surface before diffusion to the other side of the p-n junction. The dead layer leads to low carrier collection efficiency and high recombination velocity on the front surface of the cell and has adverse effects on the cell performance (Lee et al., 2013).

In a photovoltaic module, multiple solar cells of similar I-V Characteristic i.e. wattage are connected in series in order to obtain a desired voltage and power output. Partial shading of a cell in a module leads to reduction in the power output of the module. Woyte et al. (2003) investigated the shading effect due to vegetation and nearby obstacles in a 5 kW_p PV system and observed that with obstacles of irregular shape, simulation estimation is not accurate and effect of partial shading on the array performance should not be underestimated. Alonso-Garcia et al. (2006) experimentally studied the shading effects on a module and found that the deformation of the module I-V curve increases with the increase in shading and resulted in reduction in output voltage. Goss et al. (2014) developed an efficient shading loss algorithm to estimate the irradiance losses due to near and far obstructions which causes shading of both beam and diffuse irradiance and concluded that the model provides results close to measured value. Eke and Demircan (2015) analyzed the performance of two identical PV systems in building façade and analyzed the seasonal variation of energy generation due to shading on the PV systems and found that the energy rating (kWh/kW_p) differ 16% on an annual average. Belhachat and Larbes (2015) analyzed the performance of different PV array configuration under partial shaded conditions by using Simulink simulation tool and observed that Total-Cross-Tied (TCT) configurations provide the best performance under most of the partial shaded conditions. All these reported studies are focused on either the spectral variation on incident light or the effect of different shading configurations.

In this paper a completely different approach is experimentally investigated to consider the effect of individual cells of the module spectral response on shading. Spectral response, external quantum efficiency, internal quantum efficiency of the individual solar cell used in the module fabrication is analyzed. The effect of shading of the cells having highest and lowest spectral response on module output is evaluated. The diffusion length and dead layer thickness of high and low impact solar cells are calculated to emphasize the effect of spectral response on shading.

2. Theoretical formulations

The spectral response (SR) is defined as the ratio of the photogenerated current density of the solar cell to the incident photon flux and expressed as follows (Luque and Hegedus, 2011)

$$SR(\lambda) = \frac{J_{ph}(\lambda)}{G(\lambda)} \tag{1}$$

SR(λ), $J_{ph}(\lambda)$ are the spectral response and short circuit current density at a given wavelength (λ) respectively and G(λ) is the spectral irradiance of incident monochromatic light. The quantum efficiency (IQE or EQE) of a solar cell, which provides the number of charge carriers collected by the cell from the number of incident photons at a certain wavelength, can be determined from the spectral response by using the following relations (Luque and Hegedus, 2011).

$$EQE = \frac{J_{ph}}{qn_{ph}} = \frac{hc}{q\lambda} SR(\lambda) \tag{2}$$

$$IQE = \frac{1}{1 - R(\lambda)} \frac{hc}{q\lambda} SR(\lambda) = \frac{EQE}{1 - R(\lambda)} \tag{3}$$

Here, n_{ph} is the incident photon flux on the front surface of the cell, R(λ) is the reflectance of the front surface of a solar cell at wavelength λ, h is the Planck's constant, c is the speed of light and q is the electron charge. The spectral response is an important measurement which provides three parameters of solar cell viz. short-circuit current density for a given spectrum, minority carrier diffusion length of the base region and apparent dead layer (Singh et al., 2003; Michl et al., 2013). There are numerous methods to determine the diffusion length (L) of silicon solar cell of which the long wavelength spectral response (LWSR) method is used in this study. In this method diffusion length (L) is calculated from the negative intercept obtained from the linear relation between 1/IQE and inverse of silicon absorption coefficient (α_λ) at the incident monochromatic radiation (Basu and Singh, 1994; Stokes and Chu, 1977).

$$\frac{1}{IQE} - \frac{\alpha_\lambda^{-1}}{L} = 1 \tag{4}$$

The dead layer thickness (d) is calculated from the short wavelength spectral response (SWSR) and reflectance of the solar cell from the following relation (Singh et al., 1985).

$$\ln\left\{\frac{SR(\lambda)}{(1 - R_\lambda)\lambda}\right\} = -d\alpha_\lambda + \ln\left\{\frac{q}{hc}\right\} \tag{5}$$

Eq. (5) shows that a plot of $\ln\left\{\frac{SR(\lambda)}{\lambda(1-R_\lambda)}\right\}$ versus α_λ will be a straight line whose slope relative to the α_λ axis will be equal to dead layer thickness (d).

3. Experimental procedure

Multi crystalline silicon solar cells free from any visual defects are taken and sorted in terms of peak power output using a solar cells tester and sorter (Spire-Nissinbo) calibrated at standard test conditions (light intensity: 1000 W/m^2, spectrum: AM 1.5 solar spectrum, Temperature: 25 °C). From such sorted 40 numbered stack of similar wattage/power output solar cells, 36 cells are chosen arbitrarily for the present study. The spectral response curve of each cell is measured in the wavelength range of 300–1100 nm using a Bentham PVE300 system, which uses a monochromatic light to have a quick and accurate determination of solar cell spectral response. During the spectral response measurement, care has been taken so that monochromatic light (~2 mm^2) falls on the area between two fingers on the cell surface. The reflectance curves of