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Extraction of diode parameters of silicon solar cells under high illumination conditions

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ABSTRACT

An analytical method has been developed to extract all four diode parameters, namely the shunt resistance, series resistance, diode ideality factor, and reverse saturation current density, using a single *J–V* curve, based on one exponential model of silicon solar cells under high illumination conditions. The slope of the *J–V* curve (dV/dJ) at a short circuit condition is used to determine the value of the shunt resistance. The slope of the *J–V* curve at an open circuit condition together with the short circuit current density, open circuit voltage, current density, and voltage at maximum power point have been used to determine the values of the series resistance, diode ideality factor, and reverse saturation current density. The determined values of the diode parameters have been used to compute the theoretical values of the open circuit voltage, curve factor, and efficiency of the solar cell. The theoretical *J–V* curves matched well with the corresponding experimental curves. This method is applied to determine the diode parameters of concentrator silicon solar cells at different illumination conditions in a temperature range of 298–323 K. The computed values of the open circuit voltage, curve factor, and efficiency obtained using diode parameters determined with this method showed good agreement (<2% discrepancy) with the experimental values.

1. Introduction

The *J–V* characteristics of a p-n junction silicon solar cell based on a single diode model under a steady state in the IVth quadrant are described by the following equation [1–20].

$$J = -J_{ph} + J_0\left(e^{\frac{(V-JR_s)}{nV_T}} - 1\right) + \frac{(V - JR_s)}{R_{sh}} \tag{1}$$

where $V_T = kT/q$, J_{ph} = light generated current density, q = electronic charge, k = Boltzmann's constant, and T = operating temperature of the solar cell.

There are several losses in the solar cells that affect the short circuit current density J_{sc}, open circuit voltage V_{oc}, curve factor CF, and efficiency η of the cells. The parameters J_{sc}, V_{oc}, CF, and η are referred as performance parameters of the solar cells [21]. The diode parameters (i.e. shunt resistance R_{sh}, series resistance R_s, diode ideality factor n, and reverse saturated current density J_0) control the *J–V* characteristics of a solar cell at any given intensity of illumination and operating temperature of the solar cells.

The performance of as solar cell is monitored through the four performance parameters of the cell but the diode parameters dictate the values of the performance parameters at a given intensity of illumination and temperature. In fact, the diode parameters represent the different types of loss mechanisms that affect the performance of solar cells. There are four diode parameters based on the single diode model, whereas there are six diode parameters based on the double diode model. The two additional diode parameters in the double diode model are due to recombination in the space charge region. Most often, however, under normal illumination conditions, a single diode model, with the four diode parameters, adequately describes the functioning of the solar cells because of negligible recombination in the space charge region [8,22,23].

A low value of R_{sh} is due to a conductive path across the p-n junction and/or the edge of the solar cells. The R_{sh} value can affect the V_{oc}, CF, and η of the solar cells. A lower value of R_{sh} indicates more shunting loss and gives lower values of V_{oc}, CF, and η of the solar cells. R_s is the sum of the resistances of the front and back metallic contacts, the contact resistances of the metallic contact with the front and back surfaces, and the resistance of the semiconductor material. The value of n indicates the recombination in the bulk space charge regions and at the surfaces of the solar cells. A higher value of n gives a lower CF value.

However, the J_0 value is also indicative of the recombination in bulk semiconductor materials and at the surfaces of solar cells. It decisively affects V_{oc} of solar cells. A higher J_0 value results in a lower V_{oc} value, and thereby a lower value of η.

Determination of diode parameters has been studied by a number of groups [6–20,24]. Generally, most of the suggested methods [7,17,18] determine the value of R_{sh} by using the slope of the illu-

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minated I–V curve at a short circuit condition. Some of the methods evaluate the value of R_s with measurements of illuminated I–V characteristics at one [7,10,11] two [12] or many [6,13] intensities of illumination. Singh and Singh [10] used the values of illuminated current (I_L), voltage (V_m) and current (I_m) at the maximum power point to evaluate R_s. In their method [10] the value of n was assumed to fall between 2.5 and 3.0. It is thus necessary to assume the value of n or apply some other method to find the value. El-Adawi and Al-Nuaim [11] determined the values of R_{sh} and R_s using a single I–V curve. In this method it is also necessary to find the values of n and J_0. Some methods use dark I–V characteristics [14], while others utilize both the dark and illumination I–V characteristics [15] to determine the value of R_s. Rajkanan and Shewchun [15] used the dark diode voltage and the V_{oc} values corresponding to each short circuit current (I_{sc}) at different illumination intensities for evaluation of R_s. Priyanka et al. [7] determined the value of R_s using the I, V values in the 3rd and 4th quadrants along withR_{sh}, n, and I_0 (reverse saturation current) of the cells. This method [7] gives different values of R_s at different points on the I–V curve. In this case [7] the value of R_s varies with the voltage applied across the p-n junction of the solar cells. Priyanka et al.'s method [7] hence fails to determine the accurate single value of R_s that justifies the whole illuminated I–V curve at a given intensity of illumination. Del Cueto [6] determined the value ofR_s using the variation of slope at an open circuit condition with J_{sc} values. Some methods [7,16] use I_{sc}–V_{oc} characteristics to determine the values of n and I_0 of the solar cells. Khan et al. [17] used the values of I_{sc} and V_{oc}, slopes at short circuit and open circuit conditions at different illumination intensities in short spans of intensity to evaluate the values of R_{sh}, R_s, n, and I_0 of a solar cell. Phang et al. [18] used single I–V characteristics to determine all four diode parameters of solar cells at a given intensity of illumination. Their method [18], however, sometimes yields a negative value of R_s [19]. Picciano [20] determined the values of R_s, n, and I_0 using the values of I_{sc}, V_{oc}, I_m, and V_m. He [20] assumed infinite R_{sh} to determine the values ofR_s, n, and I_0. Hence, for low values of R_{sh}, this method is not able to determine the accurate diode parameter values.

The cost of solar cells can be reduced by enhancing their performance (η). The η of solar cells can be enhanced by using concentrated sunlight (under high illumination conditions). Concentrated solar cells are designed to operate under illumination greater than 1 sun. For application of concentrator solar cells, the incident intensity of illumination is increased by focusing the light using optical elements such that a high intensity light beam shines the surface of the solar cells with small area. Concentrators have several potential advantages over 1 sun in terms of enhancing the efficiency and hence allowing lower cost. The J_{sc} value of a solar cell depends linearly on the intensity of illumination. However, this effect does not enhance the η value, since the incident power also increases linearly with the intensity of illumination. The V_{oc} value of solar cells increases logarithmically with the intensity of illumination, resulting in enhancement of η. It is therefore important to determine the diode parameters to ascertain the actual performance of concentrator solar cells under high illumination conditions.

Most of the above methods are not suitable at high illumination levels because the diode parameters are not constant according to the intensity of illumination. Some numerical or curve fitting techniques have also been applied to extract all the diode parameters from a single I–V curve obtained under different illumination conditions [9,25,26]. Each of these curve fitting or numerical methods [9,25,26] uses a single I–V curve and requires special computational knowledge to determine the values of all the diode parameters of a solar cell [17]. Chan et al. [19] compared an analytical method with curve fitting and iterative methods. They [19] found that the analytical method yielded more accurate values of the diode parameters than the curve fitting and iterative methods. Khan et al. [27] investigated the variation of the values of diode parameters with intensity of illumination in an illumination range of 15–180 mW/cm^2. They [27] found that the values of the diode parameters vary with the intensity of illumination. This method [27] uses many I–V curves and gives more accurate diode parameter values than the method using a single I–V curve under normal illumination conditions [28]. It was thus shown that methods that use a single I–V curve only provide accurate values of diode parameters under high illumination conditions [29]. Hamdy [29] used the slope values at an open circuit condition and I_{sc} from a single I–V curve to determine the value of R_s at high illumination conditions. Most of the aforementioned methods are not applicable to determine the diode parameters under high illumination conditions.

In this work, we have developed a new analytical method to extract the diode parameters of concentrator silicon solar cells that is applicable at high illumination conditions. This method is based on single exponential models that uses the slope (dV/dJ) at short circuit (R_{sc}) and open circuit (R_{oc}) conditions, J_{sc}, V_{oc}, current density at maximum power point (J_m), and voltage at maximum power point (V_m). The value of R_{sc} is used to compute the value of R_{sh}. The values of R_{oc}, J_{sc}, V_{oc}, J_m, and V_m are used to extract the values of R_s, n, and J_0. At high illumination conditions, the methods based on a single I–V curve are more convenient than the methods based on many I–V curves, because there is a very small change of R_{oc} with increased intensity of illumination. In contrast, there is a fast change in the diode parameters at high illumination conditions. This method is thus applied to concentrator silicon solar cells under high illumination conditions. This method makes it possible to accurately determine all the diode parameters of silicon solar cells at higher intensity of illumination at different temperatures and under different illumination conditions. Most concentrator solar cells operate at temperature more than 298 K, and we determined the diode parameters at different temperatures in a temperature range of 298–323 K. We also investigated the variation of the diode and performance parameters with temperature under high illumination conditions.

2. Theoretical

At a short circuit condition ($V = 0$, $J = -J_{sc}$), Eq. (1) becomes

$$J_{ph} = J_0\left(e^{\left(\frac{J_{sc}R_s}{nV_T}\right)} - 1\right) + J_{sc}\left(1 + \frac{R_s}{R_{sh}}\right) \tag{2}$$

And at an open circuit condition ($V = V_{oc}$, $J = 0$), it is

$$J_{ph} = J_0\left(e^{\left(\frac{V_{oc}}{nV_T}\right)} - 1\right) + \frac{V_{oc}}{R_{sh}} \tag{3}$$

At maximum power point ($V = V_m$, $J = -J_m$) equation (1) becomes

$$J_{ph} = J_0\left(e^{\left(\frac{V_m+J_mR_s}{nV_T}\right)} - 1\right) + J_m\left(1 + \frac{R_s}{R_{sh}}\right) + \frac{V_m}{R_{sh}} \tag{4}$$

From Eqs. (2) and (3), also applying condition $R_s \ll R_{sh}$ [13,14], we obtain

$$J_0\left(e^{\left(\frac{V_{oc}}{nV_T}\right)} - e^{\left(\frac{J_{sc}R_s}{nV_T}\right)}\right) - J_{sc} + \frac{V_{oc}}{R_{sh}} = 0 \tag{5}$$

Similarly, from Eqs. (3) and (4), we get

$$e^{\left(\frac{V_{oc}}{nV_T}\right)} - J_0 e^{\left(\frac{V_m+J_mR_s}{nV_T}\right)} + \frac{V_{oc}-V_m}{R_{sh}} - J_m = 0 \tag{6}$$