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Effect of illumination intensity on cell parameters of a silicon solar cell

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ABSTRACT

The effect of illumination intensity P_{in} on the cell parameters of a silicon solar cell has been investigated based on one diode model. The variation of slopes of the I–V curves of a cell at short circuit and open circuit conditions with intensity of illumination in small span of intensity has been applied to determine the cell parameters, viz. shunt resistance R_{sh}, series resistance R_s, diode ideality factor n and reverse saturation current I_0 of the cell. The dependence of cell parameters on intensity has been investigated for a fairly wide illumination intensity range 15–180 mW/cm^2 of AM1.5 solar radiations by dividing this intensity range into a desirable number of small intensity ranges for measurements of the slopes of the I–V curves at short circuit and open circuit conditions. Initially R_{sh} increases slightly with P_{in} and then becomes constant at higher P_{in} values. However, R_s, n and I_0 all decrease continuously with P_{in}, but the rate of decrease of each of these becomes smaller at higher P_{in} values. Theoretical values of open circuit voltage V_{oc}, curve factor CF and efficiency η calculated using the cell parameters determined by the present method match well with the corresponding experimental values.

1. Introduction

The steady state I–V characteristics of a p–n junction silicon solar cell are often described based on one diode model [1–3] as

$$I = -I_{ph} + I_0\left(e\frac{q(V-IR_s)}{nkT} - 1\right) + \frac{(V-IR_s)}{R_{sh}} \quad (1)$$

In Eq. (1) I_{ph} is the light generated current, q is electron charge, k is Boltzmann constant and T is the temperature, R_{sh} is the shunt resistance, R_s is the series resistance, n is the diode ideality factor and I_0 is the reverse saturation current of the cell. R_{sh}, R_s, n, I_0 are cell parameters of the cell. These cell parameters control the I–V characteristics of a cell at any given intensity of illumination and cell temperature and thus decide the values of the performance parameters, viz. the short circuit current (I_{sc}), open circuit voltage (V_{oc}), curve factor (CF) and thereby the efficiency (η) of the cell. As the intensity of illumination changes the values of performance parameters change significantly [4–7] The dependence of performance parameters on illumination intensity can get affected if the values of the cell parameters R_{sh}, R_s, n and I_o themselves change with illumination intensity.

Therefore, it is important to evaluate all cell parameters R_{sh}, R_s, n and I_0 and study their variation with illumination intensity. Variation of the cell parameters, viz. R_{sh} and R_s with illumination intensity has been investigated analytically by several researchers [2,4,5]. However, the studies on the effect of illumination intensity on n and I_0 are rather scarce in literature [8]. Datta et al. [8] have applied a computer aided curve fitting technique to determine the values of R_{sh}, R_s, n and I_0 using I,V values corresponding to the various points on a single I–V curve obtained at a given intensity. They have determined the values of these parameters only at three values of P_{in} and their results do not show any clear trend of variation of these parameters with P_{in}.

Most silicon solar cells are designed to work under normal sunlight and their performances are evaluated at 25 °C under an AM1.5 solar irradiation of 100 mW/cm^2 intensity. Also, as stated earlier, the one diode model is most commonly used to describe the I–V characteristics of a cell. Therefore, in this work, we have investigated the variation of cell parameters based on one diode model, viz. R_{sh}, R_s, n and I_0 in the illumination intensity range 15–180 mW/cm^2. For this purpose, we divide such a wide intensity range into a large number of smaller intensity ranges, wherein the cell parameters will remain constant. We determine values of all the four cell parameters of a silicon solar cell, analytically from the variation of slopes of the I–V curve at short circuit and open circuit with P_{in} in all the smaller intensity ranges one after the other.

2. Theoretical

Denoting the slope dI/dV of I–V curve at short circuit (V=0, I= $-I_{sc}$) by m_{sc} and that at open circuit (V=V_{oc}, I=0) by m_{oc} we

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can obtain from Eq. (1) relations of slopes m_{sc} and m_{oc} with the cell parameters as

$$m_{sc}=\frac{\left[1/R_{sh}+qI_0/nkT\,e^{\frac{qI_{sc}R_s}{nkT}}\right]}{\left[1+R_s\left\{\left|1/R_{sh}+qI_0/nkT\,e^{\frac{qI_{sc}R_s}{nkT}}\right|\right\}\right]} \quad (2)$$

$$m_{oc}=\frac{\left[1/R_{sh}+qI_0/nkT/e^{\frac{qV_{oc}}{nkT}}\right]}{\left[1+R_s\left\{1/R_{sh}+qI_0/nkT\,e^{\frac{qV_{oc}}{nkT}}\right\}\right]} \quad (3)$$

Eq. (2) shows that m_{sc} is related with the diode parameters (R_{sh}, R_s, n and I_0) and I_{sc} of the cell. Similarly Eq. (3) shows that m_{oc} is related with the cell parameters and V_{oc} of the cell. Since both I_{sc} and V_{oc} depend on the intensity of illumination P_{in} we can expect both m_{sc} and m_{oc} to change with P_{in}, whether or not the cell parameters change with P_{in}.

Since a practical solar cell is designed to keep R_s small and R_{sh} large, the two conditions

$$\frac{qI_0}{nkT}e^{\frac{qI_{sc}R_s}{nkT}}\ll\frac{1}{R_{sh}} \quad (4)$$

and

$$\frac{qI_0}{nkT}e^{\frac{qV_{oc}}{nkT}}\gg\frac{1}{R_{sh}} \quad (5)$$

are satisfied simultaneously for a significantly wide P_{in} range of operation of the cell. We shall henceforth refer to it as a suitable P_{in} range. In this P_{in} range Eqs. (3) and (4) are simplified to give

$$m_{sc}{}^{-1}=(R_{sh}+R_s) \quad (6)$$

and

$$m_{oc}{}^{-1}=\left[R_s+\frac{nkT}{qI_0}\,e^{-\left(\frac{qV_{oc}}{nkT}\right)}\right] \quad (7)$$

In this P_{in} range $V_{oc}\gg I_{sc}R_s$, hence,

$$I_0e^{\frac{qV_{oc}}{nkT}}\approx I_{sc}-\frac{V_{oc}}{R_{sh}} \quad (8)$$

Substituting Eq. (8) into Eq. (7) we obtain

$$m_{oc}{}^{-1}=\left[R_s+\frac{nkT}{q}\,\frac{1}{\left(I_{sc}-\frac{V_{oc}}{R_{sh}}\right)}\right] \quad (9)$$

Also because $R_s\ll R_{sh}$, Eq. (6) can be approximated as

$$R_{sh}=m_{sc}^{-1} \quad (10)$$

The combination of Eqs. (7), (9) and (10) can be used to determine representative values of R_{sh}, R_s, n and I_0 of a cell from measurements of I_{sc}, V_{oc}, m_{sc} and m_{oc} at different intensities in a suitable range of P_{in}.

3. Experimental

The measurements for the present work were made on monocrystalline silicon (*c*-Si) solar cells of $\sim$8 cm^2 area which were fabricated using 300 μm thick, ⟨1 0 0⟩ oriented *p*-Cz silicon wafer of 1 Ω cm base resistivity. The *p*–*n* junction was made by *P*-diffusion using a $POCl_3$ liquid source. Front and back contacts were realized by screen printing Ag paste on front and Ag/Al paste on back sides of the cells. A single layer silicon nitride anti-reflection coating was given by a PECVD process using SiH_4, NH_3 and N_2 gases. Illuminated *I–V* characteristics of the cells were measured at 25 °C at different intensities in small spans of intensity which together covered a fairly wide intensity range 15–180 mW/cm^2 of simulated AM 1.5 solar radiation. The cell with its *n*+ front emitter on top was mounted on a gold plated base which was maintained at a constant temperature using a refrigerated water circulator Julabo Model F10. The cells were illuminated with a simulated AM1.5 global radiation and illuminated *I–V* characteristics were measured with the help of a KEITHLEY 2420 system sourcemeter. The illumination intensity was measured using a reference silicon solar cell obtained from PV Measurements, USA. In the following the results of measurements of cell parameters will be reported for a silicon solar cell, cell #1 fabricated as described above.

4. Result and discussion

A number of *I–V* curves were obtained for cell #1 in five small spans of intensity ranges, viz. $15<P_{in}<31$ mW/cm^2, $35<P_{in}<55$ mW/cm^2, $60<P_{in}<80$ mW/cm^2, $95<P_{in}<122$ mW/cm^2 and $145<P_{in}<180$ mW/cm^2. The values of I_{sc}, V_{oc}, m_{sc} and m_{oc} of the *I–V* curves in each of the above P_{in} ranges were used to determine the cell parameters. The value of m_{sc} was nearly invariant with intensity and thereby yielded a constant value of R_{sh} according to Eq. (10). These values of R_{sh} were in turn used with I_{sc}, V_{oc} and m_{oc} values to determine values of R_s, n and I_0 of the cell as described in the following for one intensity range, viz. $15<P_{in}<31$ mW/cm^2.

The values of m_{oc}^{-1} were plotted against $(I_{sc}-V_{oc}/R_{sh})^{-1}$ in $15<P_{in}<31$ mW/cm^2 range as shown in Fig. 1 and were fitted into a straight line represented by Eq. (9). The intercept of the straight line on m_{oc}^{-1} axis gave the value of R_s and the slope of the line with the $(I_{sc}-V_{oc}/R_{sh})^{-1}$ axis yielded the value of nkT/q. The value of nkT/q thus obtained was used in Eq. (7) and, then, the plot of m_{oc}^{-1} vs. $e^{-qVoc/nkT}$ data and their subsequent fit into a straight line as shown in Fig. 2 yielded the value of I_0 from its slope nkT/qI_0 with the $e^{-qVoc/nkT}$ axis. The intercept of m_{oc}^{-1} vs. $e^{-qVoc/nkT}$ line on m_{oc}^{-1} axis of Fig. 2 also gave a value of R_s. Thus, the values of R_{sh}, R_s, n and I_o for cell #1 were determined for $15<P_{in}<31$ mW/cm^2 range. Similarly, the values R_{sh}, R_s, n and I_o for cell #1 for the remaining four small P_{in} ranges ($35<P_{in}<55$ mW/cm^2, $60<P_{in}<80$ mW/cm^2, $95<P_{in}<122$ mW/cm^2 and $145<P_{in}<180$ mW/cm^2) were also determined. The values of the cell parameters show that the conditions (4), (5) and Eqs. (8) and (9) have been fully valid for cell #1 in all the P_{in} ranges used in the measurements. The errors are less than 0.01%. The values of R_{sh}, R_s, n and I_0 determined as above for different P_{in} ranges were assigned to the mean P_{in} value of the each P_{in} range.

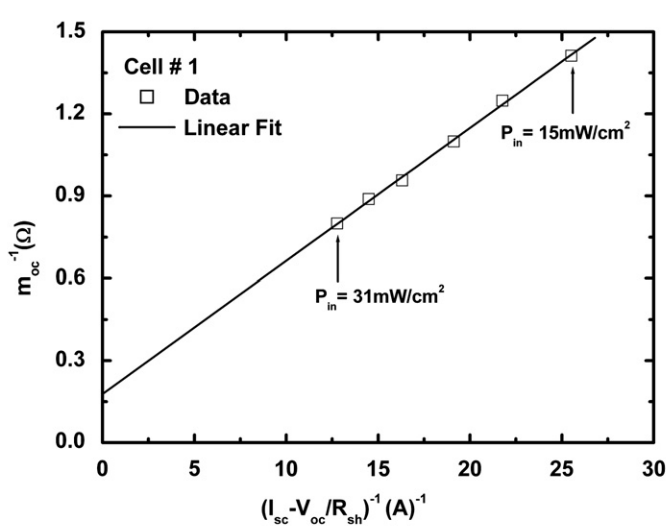

Fig. 1. Plot of m_{oc}^{-1} vs. $(I_{sc}-V_{oc}/R_{sh})^{-1}$ curve for cell #1 at $T=25$ °C and small intensity range $15<P_{in}<31$ mW/cm^2. The solid line gives a straight line fit to the data. The intercept on m_{oc}^{-1} axis gives R_s.