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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

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

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

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

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

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

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

and

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

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

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

and

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

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

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

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

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

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

$$R_{sh}=m_{sc}^{-1} \tag{10}$$

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, $\langle 1\,0\,0\rangle$ 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.

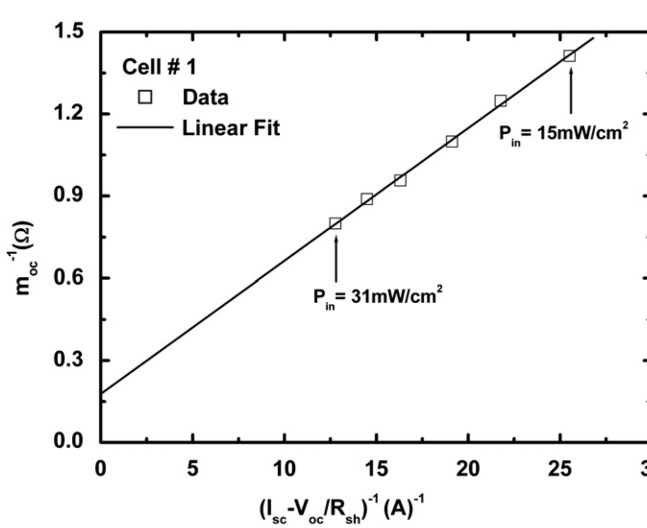

Fig. 1. Plot of m_{oc}^{-1} vs. $(I_{sc}-V_{oc}/R_{sh})^{-1}$ curve for cell #1 at T=25 °C and small intensity range $15<P_{in}<31$ mW/cm^2. The solid line gives a straight line fit to the data. The intercept on m_{oc}^{-1} axis gives R_s.

The cell parameters have been plotted against P_{in} in Fig. 3. It shows that R_{sh} increases slightly with P_{in} at lower P_{in} values and, then, becomes constant at higher intensities of illumination. Priyanka et al. [2] have also observed a similar dependence of R_{sh} on P_{in}. An increase in R_{sh} with P_{in} in the low intensity range (e.g. $P_{in} < 50$ mW/cm^2) has been observed also by Cunningham et al. [9] in PV modules based on single- and multi-crystalline silicon solar cells.

The increase of R_{sh} with P_{in} at low P_{in} values may be due to the existence of local inhomogeneities leading to non uniform current flow [10] or to charge leakage across the p–n junction in the cell [11]. This is because generally shunt is associated with the localized defect regions which in turn have a larger concentration of traps that make them electrically active [11]. These traps act as sinks for majority carriers or photogenerated minority carriers depending on the nature of the traps [12,13]. The traps can be detected using Deep Level Transient Spectroscopy [12,14]. Traps capture carriers from the neighboring regions [13]. The electrical activity of traps is stronger at low current densities under dark or at low illumination intensities. In a solar cell, a defect region makes a poor cell than the defect free region and both the cells are connected in parallel [10]. At any operational point above the short circuit, this gives rise to a circulation current. This is equivalent to a shunt current. As the illumination intensity increases the traps start getting filled and this reduces the shunt current and thus increases the shunt resistance of the cell. At a certain value of the illumination intensity, all traps get filled and then the shunt resistance attains a maximum value for further increase in the illumination intensity unless the high P_{in} causes some other effect, e.g. the heating of the cell, that may degrade the shunt resistance [15].

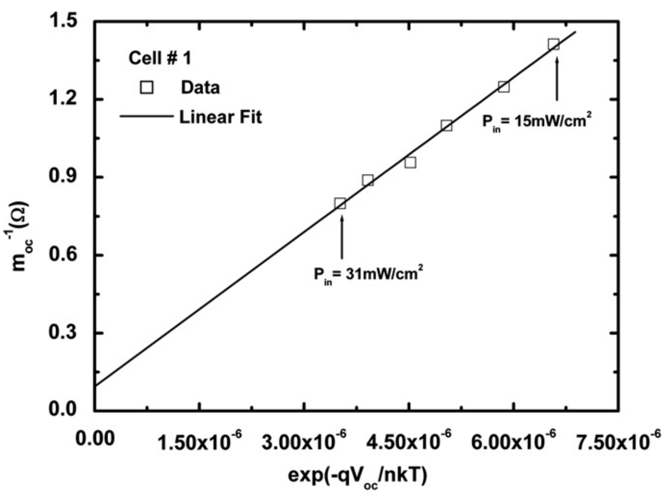

Fig. 2. Plot of m_{oc}^{-1} vs. $e^{-qVoc/nkT}$ curve for cell#1 at T=25 °C and $15 < P_{in} < 31$ mW/cm^2 with n=1.84; n was obtained from Fig. 1. The solid line gives a straight line fit to the data. The slope of straight line with the $e^{-qVoc/nkT}$ axis determines I_0 value.

Fig. 3 also shows that R_s decreases continuously with increasing the intensity of illumination. However, the rate of decrease of R_s with P_{in} is much small for $P_{in} > 70$ mW/cm^2. Earlier researchers [2,4,5,16] have also found R_s decreasing with P_{in}. As pointed out by Arora et al. [16], the decrease can be attributed it to the increase in conductivity of the active layer with the increase in the intensity of illumination.

Fig. 3 also depicts the dependence of n and I_0 with P_{in}. The values of $n > 1.5$ for $P_{in} < 40$ mW/cm^2 and decreases slowly with P_{in} from 1.5 at P_{in}=40 mW/cm^2 to 1.35 at P_{in}=160 mW/cm^2. Mcdonald and Cuevas [17] have found n decreasing with V_{oc} monotonically in multicrystalline silicon solar cells made from 1.5 Ω-cm resistivity material which implied decrease of n with P_{in}. The value of I_0 is 5.5×10^{-7} A at P_{in}=20 mW/cm^2 and decreases at higher P_{in} values. In bifacial silicon solar cells, Ohtsuka et al. [18] have observed that I_0 decreases with the increase in P_{in} under front, rear and bifacial illumination conditions.

In a silicon solar cell, the values of n and I_0 are governed by the combination of space charge recombination, bulk recombination and surface recombination mechanisms. The space charge recombination is more effective at low intensities and low junction voltages. So the higher n and I_0 values at lower intensities as shown in Fig. 3 can be attributed to the larger contribution of space charge recombination to the total recombination in the cell. The contribution of space recombination decreases at higher P_{in} and, then, the values of n and I_0 owe their values increasingly to the bulk and surface recombination mechanisms.

The values of the cell parameters shown in Fig. 3 were used in Eq. (1) along with I_{sc} values to generate theoretical I–V characteristics and calculate V_{oc}, CF and η values of cell #1 in $15 < P_{in} < 180$ mW/cm^2 intensity range. For cell #1, I_{sc}=I_{ph} has been valid in $15 < P_{in} < 180$ mW/cm^2 range. Theoretical values of

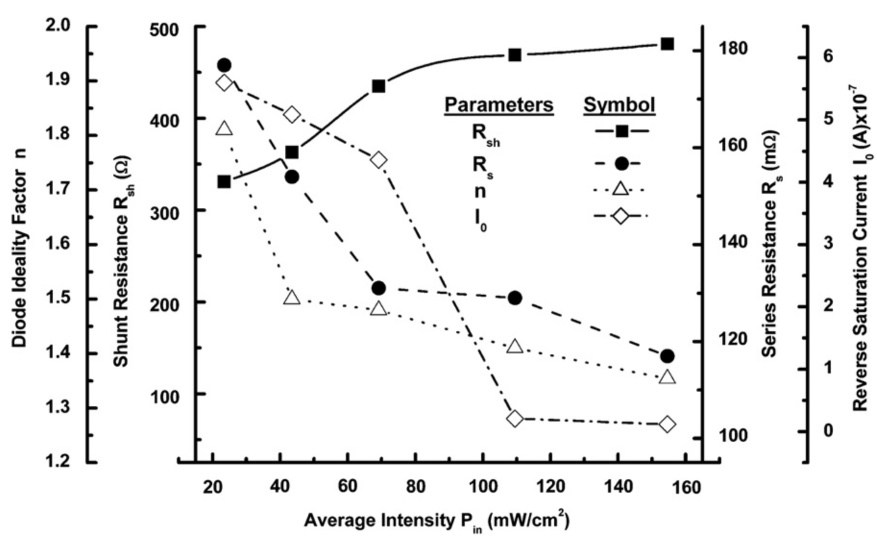

Fig. 3. Plot of the observed dependence of cell parameters viz. R_{sh} (—■—), R_s (–●–), n (···Δ···) and I_0 (···◇···) on intensity of illumination for cell #1 at T=25 °C in $15 < P_{in} < 180$ mW/cm^2 intensity range of illumination. The left- and right-end data points correspond to P_{in}=24 mW/cm^2 and P_{in}=154 mW/cm^2, respectively.

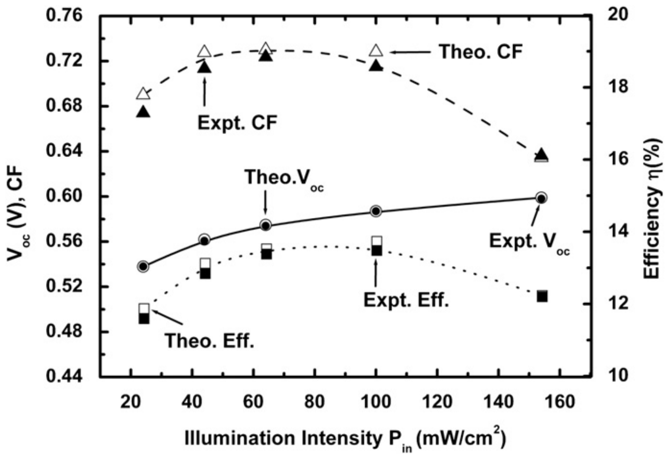

Fig. 4. Plots of the theoretical values of V_{oc} (—○—), CF (–□–) and η (..Δ..) obtained using the calculated values of the cell parameters with the experimental values V_{oc} (●), CF (■) and η (▲) at $T=25\,^{\circ}$C against intensity of illumination for $15<P_{in}<180$ mW/cm^2 range. The left- and right-end data points correspond to $P_{in}=24$ mW/cm^2 and $P_{in}=154$ mW/cm^2, respectively.

V_{oc}, CF and η are compared with the experimental values in Fig. 4. It can be noted that theoretical values of V_{oc}, CF and η match well with their experimental values obtained for $24<P_{in}<154$ mW/cm^2 range.

5. Conclusion

We have determined the values of cell parameters R_{sh}, R_s, n and I_0 using the variation of m_{sc}, m_{oc} with intensity in small P_{in} ranges and have applied this method to determine the dependence of the cell parameters with P_{in} in a fairly wide intensity range ($15<P_{in}<180$ mW/cm^2 range) by dividing it into a significantly large number of small intensity ranges. It is noted that initially R_{sh} increases with P_{in} and then become nearly constant. However, R_s, n and I_0 all decrease continuously with P_{in}. The rate of decrease of each of these parameters is higher at lower P_{in} values than at higher P_{in} values. Theoretical values of V_{oc}, CF and η obtained using the cell parameters determined by the present method match well with their corresponding experimental values. It shows that the present method of determination of the cell parameters from the slopes of I–V curve at short circuit and open circuit conditions is applicable to determine the variation of the cell parameters with P_{in} over wide P_{in} range by dividing the P_{in} range into a desirable number of small intensity ranges.

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