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Investigating the charge transport kinetics in poly-crystalline silicon solar cells for low-concentration illumination by impedance spectroscopy

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ABSTRACT

Commercially available polycrystalline silicon solar cells have been studied under varying illumination conditions to evaluate their application in low-concentration photovoltaic systems. The present work explores a detailed analytical framework for determining a broad range of performance indicating parameters for polycrystalline silicon solar cells by using the impedance spectroscopy (IS) technique. The IS measurements show that the diffusion capacitance varies from 1×10^{-7} to 5×10^{-7} F/cm^2 and diffusion resistance from 0.5 to 770 Ω-cm^2 with the applied bias. The IS measurements also indicated that the effective lifetime of charge carriers decreases with increasing illumination. This study confirms that commercially available polycrystalline silicon solar cells can work satisfactorily under low concentration (<3.5 suns).

1. Introduction

Solar energy is emerging as a renewable energy source to meet the energy demand of the next generation. The solar energy can be directly utilized for heating/cooling of fluids (i.e. solar thermal), or it can be converted into electrical energy by using solar photovoltaic (PV) cells. The direct conversion of solar radiation into electrical energy is the most suitable way of utilizing solar energy because of its convenience and diverse applications. Among the various existing semiconductor materials, silicon is the most widely used (80–90%) semiconductor for the fabrication of solar cells. At present, the price of electricity generated from silicon solar cells is somewhat higher than conventional energy sources. Further cost reduction of the solar cell is possible by using thin c-Si wafers [1], c-Si thin film [2], Si in the form of ribbon [3,4] and concentrator Si solar cells [5,6]. In the last decade, the price of silicon based solar modules has been drastically reduced making it more productive to develop low-concentration photovoltaic (LCPV) systems using these cells to achieve grid parity in the near future.

Concentrator photovoltaic (CPV) technologies are usually classified according to their concentration ratio (CR), that is, low, medium and high concentration systems [7,8]. The major challenges at medium and high concentration are: an increase in cell temperature reduces the efficiency and an accurate sun tracking system is required which increases the overall cost of the system [6]. Silicon solar cell based low concentration photovoltaic (LCPV) systems with a CR below 5 suns present two major advantages: first, LCPV systems can use conventional high performance silicon solar cells (made for 1 sun application [9]); and second, LCPV systems are less demanding in terms of tracking accuracy as compared to high concentration systems [10].

Recently, there has been a renewed interest in the low concentration silicon PV systems [11–20]. In this technology, commercial silicon solar cells are used under a concentration of 2 to 10 suns. Improvement in performance is obtained by reducing the series resistance of the solar cells using electro-deposition of high aspect ratio front metal contacts [2]. A detailed review on the modeling of low-concentration solar photovoltaics is presented by Zahedi et al. [12]. Li et al. have studied the performance of solar cell arrays based on a trough concentrating photovoltaic/thermal system [18]. Recently, Schuetz et al. [19] have reported the design and construction of ~7 × LCPV system based on compound parabolic concentrators.

Most of the studies discussed above have been performed for mono-crystalline silicon based solar cells. There is scarcity of literature on the applicability of polycrystalline silicon solar cells for low-concentration photovoltaic systems. A thorough understanding of electron kinetics is crucial in designing polycrystalline

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solar cells for LCPV applications. Close to zero-bias, the operation of an efficient solar cell is usually determined by charge separation. On the other hand at the maximum power point (close to V_{OC}), recombination kinetics (i.e. the effective recombination lifetime) play a major role [21]. The impedance spectroscopy (IS) technique is used for studying the recombination kinetics through resistance and capacitance measurements. IS is a small perturbation method that resolves the capacitive and resistive elements of electronic devices under test at steady state conditions. In the present article, commercially available polycrystalline silicon solar cells have been studied under varying illumination (i.e. varying concentration ratio, CR < 5 Sun) to find their suitability for low-concentration photovoltaic systems.

2. Theoretical modelling

2.1. Two-diode model of polycrystalline silicon solar cell

The current loss in a solar cell is governed by various recombination mechanisms [22–23] that is, (1) radiative recombination of electron-hole pairs, (2) Shockley-Read-Hall, Auger and surface recombination, (3) series and shunt resistance losses. The two-diode model used here incorporates all the above mentioned loss mechanisms and is shown in Fig. 1. The Diode 1 conducts the current arising due to the diffusion of minority carriers in the quasi neutral region of the solar cell where they recombine. The losses in the depletion region are described by Diode 2, which incorporates defect–induced charge recombination losses in the depletion region. The terminal equation for current-voltage characteristics of the solar cell is given by [24–29]:

$$I = I_{PH} - I_{D1} - I_{D2} - (V + IR_S)/R_{SH} \tag{1}$$

where I_{PH} represents the photocurrent, R_S represents the series resistance and R_{SH} represents the shunt resistance.

The diode current density in the forward bias condition can be expressed in terms of the voltage V as:

$$I_{D1} = I_i\left\{\exp\left(\frac{q(V+IR_S)}{n_1 k_B T}\right) - 1\right\} \tag{2}$$

$$I_{D2} = I_r\left\{\exp\left(\frac{q(V+IR_S)}{n_2 k_B T}\right) - 1\right\} \tag{3}$$

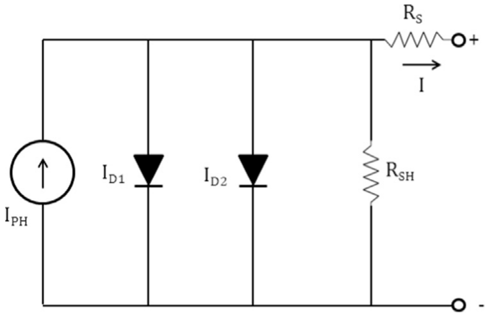

Fig. 1. The standard two diode model of a polycrystalline silicon solar cell.

where I_{D1} and I_{D2} are the current densities of diode 1 and 2 that originate from different carrier recombination mechanisms in the quasi neutral region (QNR) and the space charge region (SCR) respectively, where n_1 and n_2 are the corresponding diode ideality factors.

Generally, for solar cells under zero terminal voltage $I_{PH} \gg I_r$, I_i so in Eq. (1), the small diode currents (I_r and I_i) can be ignored. Therefore the short-circuit current (I_{SC}) is approximately equal to I_{PH}. I_{PH} mainly depends on the solar insolation and cell's working temperature by Eq. (4) [30]:

$$I_{PH} = \left[I_{SC} + K_I(T_C - T_{Ref})\right] \times CR \tag{4}$$

where, CR represents the concentration ratio, K_I is the cell's short-circuit current temperature coefficient, T_{Ref} is the cell's reference temperature and T_C is the cell's working temperature. The maximum power output (P_{MAX}) of the polycrystalline silicon solar cell is related to I_{SC} and open circuit voltage (V_{OC}) through the following equation:

$$P_{MAX} = FF \times V_{OC} \times I_{SC} \tag{5}$$

The values of I_{SC}, V_{OC} and FF can be determined from the I-V characteristics obtained by Eq. (1). The efficiency of the solar cell in relation with P_{MAX} is given by Eq. (6):

$$\eta = \frac{P_{MAX}}{(A \times \lambda)} \tag{6}$$

where, A is the area of solar cell. Based on the model described above, the electrical performance of the polycrystalline silicon solar cell is simulated using MATLAB/Simulink.

2.2. AC equivalent circuit

An AC equivalent circuit is proposed here to understand the recombination kinetics of polycrystalline silicon solar cell under illumination. The distributed elements of the proposed equivalent circuit can provide quantitative information on the diffusion and recombination mechanism associated with polycrystalline silicon solar cell. To derive the complex impedance of transmission line model (Fig. 2), it is assumed that the distributed circuit elements are position independent and charge carriers are homogeneously distributed in the solar cell [31]. The collection of charge carriers across the load terminals is dependent on the active layer thickness (L) of the device and the minority carrier diffusion length (L_n). For efficient charge collection, L_n»L, whereas the charge collection would be worst if L_n«L. The elements of the proposed equivalent circuit (Fig. 2) comprises (1) a distributed transfer resistance ($r_{tr}=R_t/L$) responsible for hindrance in the electron transport; (2) a distributed diffusion capacitance ($c_\mu=C_\mu/L$), represents the capacitance per unit area which is associated with the homogeneous accumulation of charge carriers; (3) diffusion resistance ($r_d=R_d/L$), associated with electron-hole recombination in the active layer. The effective net impedance of the above circuit elements is represented by Eq. (7) [21, 31]:

$$Z = \left(\frac{R_t R_d}{1 + i\omega/\omega_{rec}}\right)\coth\left[\left(\frac{\omega_{rec}}{\omega_d}\right)^{1/2}\left(1 + \frac{i\omega}{\omega_{rec}}\right)^{1/2}\right] \tag{7}$$

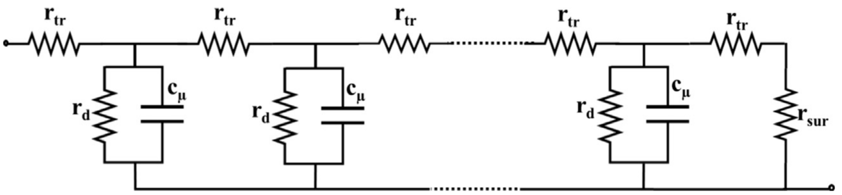

Fig. 2. Equivalent circuit (transmission line model) of polycrystalline silicon solar cell comprising of differential elements related to electron transport resistance (r_{tr}), diffusion resistance (r_d), diffusion capacitance (c_μ) and back-surface recombination resistance ($r_{sur} \to 0$) [21,31].