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Dependence of multi-junction solar cells parameters on concentration and temperature

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ABSTRACT

The dependence of InGaP/GaAs/Ge multi- junction solar cell model parameters on concentration and temperature are of interest to solar cell manufacturers. These parameters are related to cell processing and materials. In this work, the cell parameters were estimated by curve fitting of the experimental *I–V* characteristics to the single diode model equation of the multi-junction cell. The dependence of the cell parameters on light concentration and temperature is shown. Based on the estimated parameters, the performance of multi-junction cells and concentrated photovoltaic arrays under different solar irradiances and temperatures may be predicted.

1. Introduction

Concentrated photovoltaic (CPV) systems based on high efficiency multi-junction (MJ) solar cells are among the promised technologies for large scale solar electricity production. Modeling the *I–V* characteristic equation of solar cells is an important tool for the investigation of the performance of solar cells and arrays under different irradiance, temperature and solar spectrum. The *I–V* characteristic equation is an analytical expression which describes the relation between the electrical parameters of the cell and the current and voltage of the cell terminals. The use of the conventional lump-parameter single-diode model of the solar cell to predict the *I–V* characteristic equation of MJ cells at different temperatures and irradiances is reported in [1,2]. This model was used also to investigate the dependence of MJ cell performance on spectrum [3,4]. An extended model based on the five parameter model and an additional term which describes the operation of the bypass diode connected to each cell, as in CPV arrays, was shown in [5].The extended model may be used for the analysis of *I–V* characteristics of CPV dense arrays.

The single diode model equation of InGaP/GaAs/Ge MJ solar cell was used, in the present study, to estimate the five parameter values of the solar cell. Newton–Raphson algorithm was applied in the curve fitting procedure where the minimum error between the measured *I–V* cell characteristic and the theoretical cell equation served as the quality for the estimated parameters [6]. The measured *I–V* characteristics pertain to concentration of 350, 555,700 and 900 Sun and temperature of 10 °C, 25 °C, 80 °C and 95 °C. The results of the estimated parameters show a clear and a monotonic dependence of the parameter values on light concentration and on cell temperature. Based on the results, the dependence of the fill factor and the cell efficiency on concentration and temperature is also shown.

It should be emphasized that parameter estimation of solar cells based on optimization methods may lead to a local minimum. Different initial parameter values may result in different estimated parameter values. Therefore, there is no confidence in obtaining the global minimum, although the estimated parameters may have physical meanings. Adding to the procedure for estimating the parameters the notion of monotonic behavior of the parameters on different concentrations and temperatures is important to obtain confidence in the results.

2. Parameter estimation of multi-junction solar cells—Single diode model

The conventional five parameter model (single diode model) was used to estimate the parameters of the solar cell. The model is described by

$$I = I_{ph} - I_0(e^{(V+IR_s)/V_T n} - 1) - \frac{V+IR_s}{R_{sh}} \quad (1)$$

where, I and V are the terminals current and voltage, respectively, I_{ph} is the photo-generated current, I_0 is the diode reversed saturated current, n is the ideality factor of the diode, R_s and R_{sh}

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are the series and shunt resistances, respectively, and V_T is the thermal voltage. A MJ cell consists of several sub-cells (three subcells in triple-junction solar cell). Each sub-cell can be described by a five parameters model, therefore the parameters in Eq. (1) represent equivalent parameters of a MJ cell [7,8].

3. Curve fitting procedure

The Newton–Raphson algorithm was applied for curve fitting between the measured and the theoretical *I–V* characteristics at different concentrations and temperatures. The detailed algorithm is described elsewhere [6]. Since the convergence of the algorithm is very sensitive to initial parameter values, these values must be chosen carefully. In this study the initialization of the parameters is performed as described in [5]. Because the measurements contain relatively large errors near the short circuit current and the open circuit voltage, these measurements were excluded in the estimation process.

4. Results

Curve fitting was performed on the measured *I–V* characteristics of MJ* solar cells under four light concentrations: 350, 555, 700 and 900 Sun at cell temperatures of 10 °C, 25 °C, 80 °C and 95 °C. A very good fit was achieved for all cell measurements. A comparison between the measured to the fitted *I–V* characteristic for concentration of 900 Sun at 95 °C is shown in Fig. 1, as an example. The results prove that the single diode model may be used to describe the *I–V* characteristic of a MJ solar cell at different concentrations and temperatures. Although the model is an analytical expression and does not necessarily describe accurately physical mechanisms inside the cell, some of the equivalent cell parameters may have practical values.

4.1. Dependence of solar cell parameters on light concentration

Based on the proposed curve fitting procedure, the dependence of the estimated parameters on the light concentration was studied. Fig. 2a shows a linear dependence of I_{ph} on light concentration, E, as expected [9]:

$$I_{ph}(E)=I_{ph}(E_0)\times\frac{E}{E_0} \tag{2}$$

where, $E_0=1$ Sun (1000 W/m^2). The increase of I_{ph} with light concentration is higher for high temperatures due to the reduction of the subcells bandgap resulting in a higher absorption. The saturation corrent, I_0 (Fig. 2b) and the ideality factor, n (Fig. 2c) increase with light concentration. The I_0 and n of a solar cell are directly related to equivalent recombination processes in the cell (space charge recombination, bulk recombination and surface recombination) [10]. A solar cell with a higher recombination (lower carriers lifetimes) has larger I_0 and n. The reverse saturation current, I_0, of an ideal *p–n* diode is given by [10]

$$I_0=q\left(\sqrt{\frac{D_p n_i^2}{\tau_p N_D}}+\sqrt{\frac{D_n n_i^2}{\tau_n N_A}}\right) \tag{3}$$

where q is elementary charge, A is the cross-sectional area, D_p and D_n are the diffusion coefficients of holes and electrons, respectively, N_A and N_D are the donor and acceptor concentrations at the n and p sides, respectively, n_i is the intrinsic carrier concentration of the semiconductor material, and τ_p and τ_n are the carrier lifetimes of holes and electrons, respectively. As the light concentration increases, the recombination processes are enhanced, especially the radiatiave and Auger recombination. This eventually

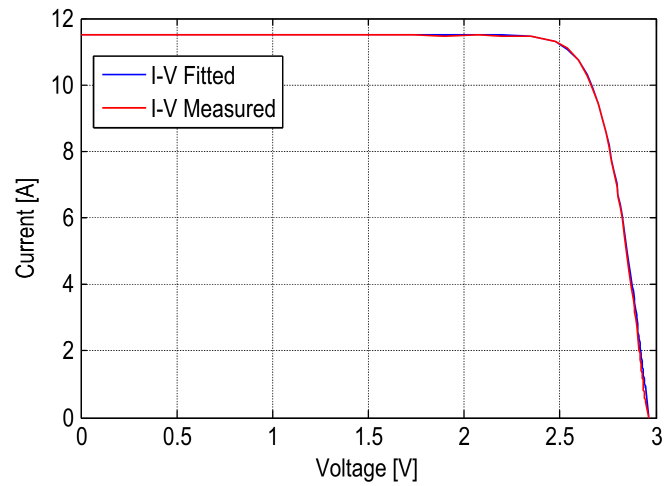

Fig. 1. Measured and fitted *I–V* characteristic of MJ cell at 900 Sun and 95 °C. *Data provided courtesy by Spectrolab Inc.

limits the cell efficiency [11] and leads to a decrease of the total carrier lifetimes $\tau_{p/n}$ and, as a result, to an increase of I_0. Therefore, the increase of n might be related to the increase in the Auger and radiative recombination mechanisms.

The dependence of the R_s and R_{sh} on the light concentration is shown in Fig. 2d and e. As the light concentration increases, the values of R_s and R_{sh} decrease. The R_s is strongly dependent on the resistance of the semiconductor layers, on the contact resistance at the semiconductor–metal interface, on the resistance of the metal gridlines, as well as on the tunnel diodes resistivities [12]. The reduction of R_s with the light concentration may be explained by the change in the material resistivity. The resistivity ρ (the inverse of the conductivity σ) is given by [13]

$$\rho=\frac{1}{\sigma}=1/q(\mu_n n+\mu_p p) \tag{4}$$

where n and p are the electron and hole concentration and μ_n and μ_p are the electron and hole mobility (material dependent), respectively. As light concentration increases, the charge carriers concentration of electron and holes increases as well and, therefore the material resistivity and hence the series and shunt resistance, decrease. The decrease of the shunt resistanceR_{sh} is a result of higher leakage currents at high light concentration [14].

4.2. Dependence of solar cell parameters on cell temperature

Temperature affects the five parameter model equation in two ways: directly, via the explicit T in the exponential term, and indirectly via the change in the parameters with temperature.

The dependence of I_{ph} on temperature is shown in Fig. 3a. The equivalent I_{ph} of the cell is influenced from the light absorption, i.e., charge carrier generation in the cell. As the temperature increases the bandgaps, $E_g(T)$, of all subcells shrink as described by Varshni's empirical expression [13]

$$E_g(T)=E_g(0)-\frac{\alpha T^2}{T+\beta} \tag{5}$$

where, $E_g(0)$, α and β are material constants. Therefore, since $E_g(T)$ decreases, more photons have the sufficient energy to create electron–hole pairs and therefore I_{ph} increases. The value of I_0 increases exponentially with tempearture (Fig. 3b) mainly due to the increase in the intrinsic carrier concentration, n_i [15], as shown in Eq. (3). The intrinsic carrier concentration [15] is given by

$$n_i=N_s e^{-(E_g/2k_BT)} \tag{6}$$