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Extraction of solar cell series resistance without presumed current–voltage functional form

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ABSTRACT

A new method which does not require presumed current–voltage functional form is proposed for the determination of the series resistance, the shunt resistance, the photocurrent, and the intrinsic current–voltage characteristics of solar cells. This method was applied to analyze a bulk heterojunction organic solar cell. It was found that the extracted intrinsic current–voltage characteristic clearly exhibits a linear hopping current component and a quadratic space-charge limited current component. Furthermore, the reconstructed dark current–voltage curve is found to differ significantly from the measured dark current–voltage curve, revealing the importance of electric field in the operation of bulk heterojunction organic solar cells.

1. Introduction

Solar cells are promising devices for clean electric generation and have attracted intensive research. Like all other electrical power generators, solar cells possess internal series resistance which affects significantly their power conversion efficiency (PCE). Moreover, the simulation and design of solar cell systems also require an accurate knowledge of the series resistance and other related device parameters to describe their nonlinear electrical behavior. Extracting the series resistance as well as other device parameters for solar cells is therefore of vital importance.

Over the years, various methods have been proposed for extracting the series resistance and related device parameters of solar cells [1–13]. These methods either involve current–voltage (*I–V*) measurements with different illumination levels [1–3,8], or apply curve fitting method to some presumed functional relationship [5–7,9–12], or employ integration procedures based on the computation of the area under the *I–V* curves [4], or use linear regression [13].

However, all these previously proposed methods are based on the assumption that the intrinsic *I–V* relationship of the solar cell follows a specific functional form, which is usually taken to be one or combination of the Shockley-type single exponential *I–V* characteristic with ideality factor. While the exponential *I–V* assumption may produce convenient equivalent-circuit model for use in conventional simulation tools, its validity, and hence its usefulness in understanding the underlying physics, is generally not guaranteed. This is especially the case for non p–n junction type devices such as organic solar cell (OSC) or dye-sensitized solar cell. For example, one would expect polynomial type intrinsic *I–V* characteristics for OSC if the charge transport is dominantly space-charge-limited (SCL). It is therefore advantageous to be able to extract the series resistance and device parameters without presumed *I–V* functional form. Such a series resistance extraction method without presumed *I–V* functional form is proposed in this paper. We found that with certain physically plausible assumptions such a scheme will lead to unique determination of all the device parameters as well as the intrinsic *I–V* characteristics. This method was applied to OSC and first-order hopping current and second-order SCL current components were observed in the intrinsic *I–V* characteristics.

2. Theory

The solar cell is characterized using the equivalent circuit model as shown in Fig. 1 and the relation between the measured current I_m and the measured voltage V_m is given by

$$I_m = \frac{V_D}{R_{sh}} + f(V_D) - I_{ph} \tag{1}$$

$$V_m = V_D + \left[\frac{V_D}{R_{sh}} + f(V_D) - I_{ph}\right] \cdot R_s \tag{2}$$

where V_D, $f(V_D)$, I_{ph}, R_s and R_{sh}, are the voltage across the diode, the intrinsic *I–V* characteristics of the diode, the photocurrent, the

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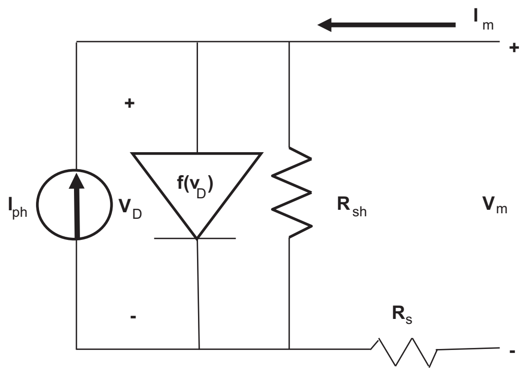

Fig. 1. The circuit model for solar cells.

series resistance and the shunt resistance, respectively. Note from Fig. 1 that since both $f(V_D)$ and R_{sh} are to be determined and are in parallel connection, any combination of $f(V_D)$ and R_{sh} that preserves the value $V_D/R_{sh}+f(V_D)$ will leave the measured I–V characteristics, I_m and V_m, unchanged. One therefore needs more assumptions to allow for unique determination of these device parameters. The following for assumptions are taken in our fitting scheme:

1. R_s, R_{sh}, I_{ph} remain constant during the measurements;
2. $f(0)=0$, that is, the power generation is all attributed to I_{ph};
3. $f(V_D) \to -f_0$ as $V_D \ll 0$; that is, the leakage current is attributed to R_{sh};
4. $f(V_D)$ is a monotonic function of V_D;
5. $f(V_D)$ is nonlinear for $V_D > 0$;
6. I_{ph} changes monotonically with illumination level.

From assumption 4 and (2), V_m is also a monotonic function of V_D, and $V_m \ll 0$ when $V_D \ll 0$. From assumption 3 for $V_m \ll 0$, one can eliminate V_D from both (1) and (2) and obtain

$$I_m = \frac{1}{(R_{sh}+R_s)} \cdot V_m - \frac{R_{sh}}{(R_{sh}+R_s)} \cdot (f_0+I_{ph}) \quad (3)$$

The total resistance $R_t=R_{sh}+R_s$ can therefore be obtained from the slope dI_m/dV_m at $V_m \ll 0$.

From (1) and (2) one can obtain

$$V_D = V_m - R_s \cdot I_m \quad (4)$$

$$f(V_D) = \frac{R_t}{(R_t-R_s)} \cdot I_m - \frac{V_m}{(R_t-R_s)} + I_{ph} \quad (5)$$

Considering also assumption 2, one also has

$$I_{ph} = -I_m(V_m @ V_D=0) \quad (6)$$

It is clear from (3), (4) and (5) that since R_t can be extracted from the measured I–V characteristics, once R_s is determined, all other device parameters, namely R_{sh}, I_{ph} and the intrinsic I–V characteristics $f(V_D)$ can all be extracted. We now need a scheme to determine R_s.

In order to devise a scheme for the unique determination of R_s, we construct the following test quantities for arbitrary R:

$$V_{DR} = V_m - R \cdot I_m \quad (7)$$

$$I_{phR} = -I_m(V_m @ V_{DR}=0) \quad (8)$$

$$f_R = \frac{R_t}{(R_t-R)} \cdot I_m - \frac{V_m}{(R_t-R)} + I_{phR} \quad (9)$$

Denote as V_{D0} the voltage across the diode when $V_{DR}=0$. It is clear that if $R=R_s$, then V_{DR}, f_R and I_{phR} reduce to V_D, f and I_{ph}, respectively, and $V_{D0}=0$.

For $R \neq R_s$, as derived in appendix, we have the following three equalities:

$$f(V_{D0}) = \frac{(R_t-R)}{R_{sh} \cdot (R-R_s)} \cdot V_{D0} + I_{ph} \quad (10)$$

$$f_R = \frac{R_{sh}}{(R_t-R)} \cdot (f(V_D) - f(V_{D0})) \quad (11)$$

$$f_R = \frac{R_{sh}}{(R_t-R)\cdot(R_s-R)} \cdot V_{DR} + \frac{1}{(R-R_s)} \cdot (V_D - V_{D0}) \quad (12)$$

It is obvious from (10) that V_{D0} depends on both I_{ph} and R.

For a given $f(V_D)$, one can expand it into Taylor series around V_{D0},

$$f(V_D) = f(V_{D0}) + f'(V_{D0}) \cdot (V_D - V_{D0}) + \frac{1}{2!} f''(V_{D0}) \cdot (V_D - V_{D0})^2 + \cdots \quad (13)$$

Combining (11)–(13), we have

$$\frac{R_{sh}}{(R_t-R)(R_s-R)} V_{DR} + \frac{1}{(R-R_s)} (V_D - V_{D0}) = \frac{R_{sh}}{(R_t-R)} \left[f'(V_{D0})(V_D-V_{D0}) + \frac{1}{2!} f''(V_{D0})(V_D-V_{D0})^2 + \cdots \right] \quad (14)$$

For a given $f(V_D)$, one can solve (V_D-V_{D0}) from (14) and substitute the result into (12) to obtain the functional relationship between f_R and V_{DR}. Since, from 5, $f(V_D)$ is nonlinear in V_D, the coefficients in the expansion (13) cannot be all constant and must depend on V_{D0}. Therefore, (V_D-V_{D0}) and hence f_R must also depend on V_{D0}.

From the aforementioned discussion, we know that unless $R=R_s$, at which V_{D0} vanishes identically, $f_R(V_{DR})$ must depend on V_{D0} and hence on I_{ph} and illumination level (6). At a specific R, we may therefore use the root-mean-square error (RMSE) between $f_R(V_{DR})$ at different illumination levels to determine if R coincides with R_s. Alternatively one may use the extracted $f_R(V_{DR})$ from the I–V measurement at one illumination level to reconstruct the measured I–V at another illumination and calculate the RMSE. It is noteworthy that to avoid the temperature difference due to different illumination levels, which might lead to significant extraction error [12,14], it is suggested that close illumination levels are used. In practice close illumination levels also ensure the constancy of R_s, R_{sh} required in assumption 1 and ascertain that identical R_t from both I–V characteristics can be obtained. Since R_s and R_{sh} are sensitive to cell temperature and illumination level, the constancy of R_t is an important indicator that assumption 1 is met. Note also that our extraction algorithm does not require the precise ratio in the illumination levels.

Our R_s extracting scheme is summarized as follows:

1. measure I–V characteristics $I_{m1}(V_m)$ and $I_{m2}(V_m)$ at two different illumination levels;
2. extract R_t from both $I_{m1}(V_m)$ and $I_{m2}(V_m)$ according to (3);
3. for a given R construct V_{DR1}, f_{R1} and I_{phR1} according to (7)–(9) from $I_{m1}(V_m)$;
4. extract I_{phR2} according to (7) and (8) from $I_{m2}(V_m)$;
5. reconstruct $I_{reconstruct2}(V_m)$ from V_{DR1}, f_{R1} and I_{phR2};
6. calculate the RMSE between $I_{m2}(V_m)$ and $I_{reconstruct2}(V_m)$;
7. repeat 3–5 for another R and search for minimum of RMSE.

Although too straightforward to be included in this paper, we have checked the validity of this fitting scheme (steps 3–7) with numerically generated data. It was found that the discrepancy in the fitting result was set by the error in the estimated R_t. It is therefore advisable to estimate R_t at sufficiently negative bias.