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Analysing Solar Cells by Circuit Modelling

Siyu Guo*a, Fa-Jun Ma, Bram Hoex, Armin G. Aberle, Marius Peters

*Solar Energy Research Institute of Singapore, National University of Singapore, 7 Engineering Drive 1, Block E3A, Singapore 117574, Singapore
Fraunhofer Institute for Solar Energy Systems ISE, 79110 Freiburg, Germany

Abstract

Solar cell models implemented in simulation packages (for example Sentaurus TCAD) are typically restricted either to only one or two dimensions, or to small scales. They therefore neglect effects of local inhomogeneities or large-scale phenomena such as lateral transport to fingers or busbars. In this paper, we use a distributed circuit model to investigate lateral inhomogeneity effects on silicon wafer solar cells. The circuit is constructed of different unit elements based on the one-diode model. To calculate the characteristics of the circuit, we use the freely available software LTspice IV (Linear Technology Corp). The presented model is used to simulate the distributed current flow in a solar cell. First, the design of the distributed circuit model is described. Then, the current-voltage characteristics obtained by the distributed circuit model are compared with those obtained from measurements. Finally, one kind of large-scale lateral effect, the voltage distribution across the solar cell area, is analysed. Due to lateral ohmic voltage drops, the electric potential at the cell surface is shown to be higher in the middle between two busbars or fingers than close to them.

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* Corresponding author. Tel.: +65 8481 6719; fax: +65 6777 1943
E-mail address: guo_siyu@nus.edu.sg

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1. Introduction

Spatial variations of the electronic properties of solar cells often have influence on the solar cell device performance. These variations can be found on every level of the solar cell device. The theoretical investigation of large-scale variation is challenging since simulation packages for solar cell modelling are often restricted to one dimension (e.g. PC1D [1]) or they are limited to small scales compared to the entire device (e.g. Sentaurus TCAD [2]). One extension to these methods to investigate large-scale effects are analytical models. An example is the use of the one-diode equation to investigate the lumped series resistance $R_s$ [3]. In this model, all series resistances are lumped together into one effective series resistance. However, this approach does not allow investigating local effects.

In order to resolve these issues, different kinds of distributed models have been proposed. Zekry and Al-Mazroo [4] have introduced a distributed SPICE model of a solar cell in order to solve the problems of inhomogeneous current distribution. Grote et al. [5] have analysed the effects of laterally varying emitter sheet resistance in combination with contact resistance. In Ref. [6], the effects of lateral inhomogeneities of the silicon solar cells themselves as well as externally introduced lateral inhomogeneities during the measurement process on measurement results are analysed by the same group. Steiner et al. [7] have used a distributed network model for the optimisation of the front contact grid structure.

In this paper, a 2D electrical network of diodes and resistors, i.e., a distributed circuit model, has been constructed to describe large-scale lateral effects. The implementation of the model has been done according to Ref. [6]. Certain aspects have been taken from Refs. [4] and [7]. The implemented model has been tested and calibrated with one-sun I-V measurement taken from Si wafer solar cells produced at SERIS to verify and calibrate our model. In a second step, the local voltage distribution between two fingers and two busbars of the front grid is investigated.

2. The Model

In this work a distributed circuit model was used to investigate the voltage distribution on the front surface of a silicon wafer solar cell. LTspice [8] was used for the circuit simulations in this work. A great variety of electronic components are provided in this software, such as constant current sources, constant voltage sources, resistors, diodes and capacitors. The solar cell was divided into identical segments in which the current distribution is the same. One segment is a 2D network of electric components, and the range of the segment is shown by the red rectangle in Fig. 1. Each segment consists of about 150 elementary units which are based on the one-diode model. Each unit is composed of a current source, a diode, a shunt resistance and series resistances such as emitter resistance, contact resistance and the resistance of the front metallisation. Resistances both in direction perpendicular to fingers and in direction parallel to fingers are taken into consideration in order to simulate the effects of 2D current flow in this network.
The one-diode equivalent circuit of a solar cell is shown in Fig. 2. It consists of a diode, a current source, a lumped series resistance and a shunt resistance. The current source generates the photo-current ($J_{ph}$) which is a function of the incident solar irradiation and the solar cell temperature. The diode represents the p–n junction. The diode is described by the reverse saturation current ($J_s$) and the constant diode ideality factor ($n$). This voltage loss due to the charge carrier transport is described by a series resistance ($R_s$). Furthermore leakage currents are described by a shunt resistance ($R_{sh}$). Using Kirchhoff’s first law, the equation for the extended J-V curve can be derived as follows [9]:

$$J = J_{ph} - J_s \exp \left[ \frac{q(V + IR_s)}{nkT} \right] - \frac{V + IR_s}{R_{sh}}, \quad (1)$$

where $J$ is the output current of a solar cell, $V$ its terminal voltage, $q$ the electronic charge ($1.6 \times 10^{-19}$ C), $k$ the Boltzmann constant ($1.38 \times 10^{-23}$ J/K) and $T$ the cell temperature (K).

The model parameters for each unit are assigned according to its position and the model geometry. The only inhomogeneity in this model is given by the front metallisation. Units underneath the metallisation grid include a front contact to which they are connected by a contact resistance. Additionally it is assumed, that these units are not illuminated (no current source). Figure 1 also shows the model of a solar cell and two intersections through a segment. The upper picture shows the intersection between two fingers, the picture on the right hand side shows the intersection along a finger.
3. Results

3.1. Comparison between simulated and measured current voltage characteristics

To validate and calibrate the model used in this work, the illuminated current-voltage characteristics obtained from the distributed circuit model were compared to the ones obtained from measurement. The parameter values shown in Table 1 were used to define the input parameters of each element. The photo current, reverse saturation current, shunt resistances and ideality factor of the diode are obtained by fitting the current-voltage curve obtained from the one-diode model to the current-voltage curve generated by PC1D. The series resistances depend on the geometry and position of each node, and they are calculated from measured parameter values shown in Table 1, including $w_b$, $l_f$, $d_f$, $h_b$, $\rho_c$, $\rho_m$ and $R_{sheet}$. In a real solar cell the current is generated continuously in the illuminated area, however, in the distributed circuit model, the current flow is discrete. In order to compensate for this model imperfection, a correction factor [6] is taken into consideration when calculating the emitter sheet resistances between two fingers in direction perpendicular to fingers and the metal resistances of the fingers in direction parallel to fingers.

Table 1. Solar cell parameters used in the simulation of this work. $j_{sc}$ is the short-circuit current density, $j_i$ is the reverse saturation current density, $w_b$ is the width of a busbar, $w_f$ is the width of a finger, $l_f$ is the length of a finger, $d_f$ is the distance between two fingers, $h_b$ is the height of a busbar, $h_f$ is the height of a finger, $\rho_c$ is the contact resistance, $\rho_m$ is metal resistivity, $R_{sheet}$ is emitter sheet resistance, $n$ is the ideality factor of a diode, $T$ is temperature. Among them, $w_b$, $l_f$, $d_f$, $h_b$, $\rho_c$, $\rho_m$ and $R_{sheet}$ are obtained from measurement, and $j_{sc}$, $j_i$, $n$ are fitting values.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$j_{sc}$</th>
<th>$j_i$</th>
<th>$n$</th>
<th>$T$</th>
<th>$R_{sheet}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>36.98 mA/cm$^2$</td>
<td>$10^{-11}$ A/cm$^2$</td>
<td>1.1</td>
<td>298.15 K</td>
<td>70 Ohm/sq</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$\rho_c$</th>
<th>$\rho_m$</th>
<th>$h_f$, $h_b$</th>
<th>$l_f$</th>
<th>$d_f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>0.003 Ohm cm$^2$</td>
<td>$3.5 \times 10^{-6}$ Ohm cm</td>
<td>0.00145 cm</td>
<td>5.05 cm</td>
<td>0.203 cm</td>
</tr>
</tbody>
</table>

The results of this comparison are shown in Fig. 3. Note that the simulated current-voltage characteristics have not been fitted but were calculated using the parameters established previously. When comparing the results from the distributed circuit model and measurement results, very similar current-voltage characteristics are observed. In Table 2, the differences between the 1-sun current-voltage characteristics obtained from the distributed circuit models and the ones obtained from measurement are calculated. The differences between $j_{sc}$, $V_{oc}$ and fill factor are all less than 1%. This shows that the distributed circuit model works well in describing the electrical characteristics of a solar cell.

Table 2. Solar cell characteristics of measurement and distributed circuit model and relative deviation

<table>
<thead>
<tr>
<th></th>
<th>Measurement</th>
<th>Circuit model</th>
<th>Relative difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$j_{sc}$ (mA/cm$^2$)</td>
<td>37.0</td>
<td>37.0</td>
<td>0</td>
</tr>
<tr>
<td>$V_{oc}$ (V)</td>
<td>0.624</td>
<td>0.626</td>
<td>0.32</td>
</tr>
<tr>
<td>Max power (mW/cm$^2$)</td>
<td>18.10</td>
<td>18.27</td>
<td>0.94</td>
</tr>
<tr>
<td>FF (%)</td>
<td>78.4</td>
<td>78.9</td>
<td>0.64</td>
</tr>
</tbody>
</table>
3.2. Voltage distribution on the surface

The voltage value of an arbitrary position in the 2D network can be obtained from the simulation results. The voltage distribution between two fingers and two busbars, calculated at the maximum power point under one-sun illumination, are shown in Fig. 3. Figure 3(a) shows the voltage distribution between two fingers and Fig. 3(b) the voltage distribution between two busbars. The parameter values of Table 1 were used in these calculations, except for the finger length, which was changed to \( l_f = 3.0 \) cm and the distance between two fingers, which was changed to \( d_f = 0.21 \) cm. Between two fingers, the voltage first increases, reaches a maximum in the middle between two fingers, and then decreases again. This is not unexpected and can be attributed to the lateral transport of charge carriers. The driving force required to move the charge carriers to the fingers is larger in the middle between two fingers than in the area close to the fingers. Between two busbars, the voltage increases from one busbar to the middle of two busbars, and reaches its maximum at the middle of two busbars. Similarly, the driving force required to move the charge carriers to the busbars is larger in the middle of two busbars than in the area close to the busbars.
4. Conclusion and outlook

In this contribution, a distributed circuit model was described and results obtained by this model, investigating the voltage distribution between two fingers and two busbars, were presented. In a first step we verified our model by comparing it to measured results. When using input parameters derived from measurements, we found good agreement between simulation and measurements. This shows that the model works effectively. All one-sun current-voltage parameters derived from modelling and experiments were within 1%, hence, well within the measurement uncertainty.

Additionally, we investigated the local voltage distribution between two fingers and two busbars. The difference in voltage here is due to differences in the driving force required to drive out the charge carriers. This is an effect caused by the lateral transport of charge carriers and is therefore multidimensional and large-scale. This effect cannot be simulated with PC1D, and only with great difficulties in a complete solar cell simulation like Sentaurus TCAD. With the distributed circuit model the expected characteristics, a higher voltage in the middle between two fingers or two busbars than close to them, could be reproduced. The calculation time to obtain this result was in the order of 15 minutes. This shows the potential of circuit simulations for the investigation of multidimensional or large-scale effects.

In the future work, we plan to investigate more local inhomogeneity effects of silicon wafer solar cells by this distributed circuit model, such as the influences from a laterally inhomogeneous emitter and the influences from a laterally non-uniform illumination. Also, the influences from local shunts can potentially be analysed by simulating the voltage distribution and current distribution in 2D.

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References


