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Investigating Local Inhomogeneity Effects of Silicon Wafer Solar Cells by Circuit Modelling

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Abstract

Local inhomogeneity effects such as shunts, inhomogeneous sheet resistance and inhomogeneous recombination rate are typical phenomena for silicon wafer solar cells. Some widely used solar cell simulators (for example Sentaurus TCAD and PC1D) have limitations in modelling these effects, since they are, for practical reasons, often restricted either to only one or two dimensions, or to small scales. In this work, circuit modelling is used to simulate local inhomogeneity effects of a silicon wafer solar cell. A distributed circuit model has the advantage that it can take large-scale lateral transport of carriers into account. First, the method of constructing the distributed circuit model is described. Then some local inhomogeneities, such as local shunts and broken fingers, are introduced into the circuit model. Finally, the global *I-V* characteristics and voltage distribution of the modelled cell are calculated. It is found that local inhomogeneities have an influence on the efficiency of a solar cell, and that this kind of influence can be quantified by circuit modelling. For example, it was calculated that a broken finger reduced the fill factor of the simulated solar cell by about 1.1% relative, and local shunt reduced the fill factor by about 3.2% relative.

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Keywords: Solar cell; circuit modelling; inhomogeneity

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1. Introduction

Local inhomogeneity effects are typical phenomena for silicon solar cells and they influence the solar cell device efficiency. The theoretical analysis of these effects on large scales is unachievable for some widely-used solar cell simulators, since they are typically either limited to small scales (e.g. Sentaurus TCAD) or to one dimension (e.g. PC1D). In this work, a distributed circuit model that is used to simulate large-scale transport effects is discussed. Two large-scale local inhomogeneity effects on silicon wafer solar cells are investigated: hot spots and broken fingers. The distributed circuit model is built in LTSPICE IV (Linear Technology Corp.) [1], which is a freely available circuit simulator.

Circuit modelling for solar cells based on diode models is a well-established technique and has been used to investigate various scientific questions before. In Ref. [2], a distributed SPICE model of a solar cell was introduced by Zekry and Al-Mazroo in order to solve the problems of inhomogeneous current distribution. Grote *et al*. analysed the effects of laterally varying emitter sheet resistance in Ref. [3], and also investigated effects from externally introduced lateral inhomogeneities during the measurement process in Ref. [4]. Yang *et al*. [5] used a distributed network model built in PSPICE to optimise the front contact grid structure. In Ref [6], a distributed emitter model for solar cells was built by Haas *et al*. to extract an equivalent lumped series resistance. Galiana *et al*. [7] constructed a 3-D distributed circuit model for concentrator solar cells and simulated the external connections and non-uniform illumination profiles.

In this paper, we first describe our method for constructing a distributed circuit model of a silicon wafer solar cell. Subsequently, two kinds of local inhomogeneities - local shunts and broken fingers - were introduced into the circuit model. Finally, the effects of these inhomogeneities on the solar cells' characteristics are discussed. It is found that local inhomogeneities mainly have an influence on the fill factor.

2. Method

In this work, we implemented a circuit of about 1200 unit elements using the open-source software LTSPICE [1]. The implementation of the model is based on procedures presented in Refs. [2], [4] and [8]. A great variety of electronic components are provided in LTSPICE, such as constant current sources, constant voltage sources, resistors, diodes and capacitors. The circuit constructed and investigated in this work was a 2D section of the surface of a solar cell with a total simulated area of 4.5 cm^2. It included five fingers and one busbar. Each unit element was based on the one-diode model which included a current source, a diode, a shunt resistance and a series resistance. Additional elements represented the front metal grid and the contact resistance between grid and solar cell. Resistances both in direction perpendicular to fingers and in direction parallel to fingers were taken into consideration in order to simulate the effects of a current flowing in this 2D network. The model parameters for each unit were assigned according to its position and the model geometry. The only inhomogeneity in this model was given by the front metallisation. Units underneath the metallisation grid included a front contact to the metallisation by a contact resistance. Additionally it was assumed, that these units were not illuminated (no current source). Figure 1 shows the structure of the simulated solar cell and two intersections. The graph on the left shows the intersection between two fingers, and the graph on the right shows the simulated area. The parameters used in this simulation are summarised in Table 1.

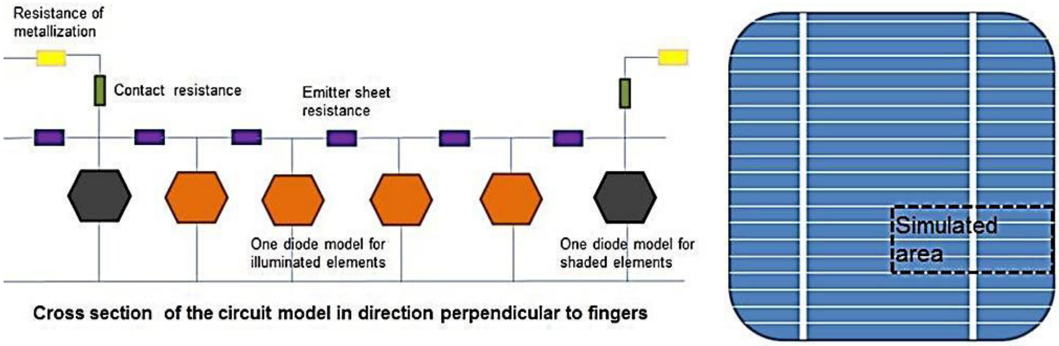

Fig. 1. Structure of the circuit model used in the simulation of this work. The cross section of the circuit model between two adjacent fingers is shown on the left, and the simulated part of a solar cell is shown on the right.

Table 1. Solar cell parameters used in the simulation of this work. j_{sc} is the short-circuit current density, j_s 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, ρ_C is the contact resistance, ρ_M is metal resistivity, R_{sheet} is emitter sheet resistance, n is the ideality factor of a diode, T is temperature. Among them, w_f, w_b, l_f, d_f, h_b, ρ_C , ρ_M and R_{sheet} were obtained from measurement, and j_{sc}, j *and, n* were fitting values.

Parameter	j_{sc}	j_s	n	T	R_{sheet}	w_b
Value	40.0 mA/cm^2	10^{-12} A/cm^2	1.02	298.15 K	70 Ohm/sq	0.09 cm
Parameter	ρ_C	ρ_M	h_f, h_b	l_f	d_f	w_f
Value	0.003 Ohm cm^2	3.5×10^{-6} Ohm cm	0.00145 cm	5.05 cm	0.203 cm	0.013 cm

The one-diode equivalent circuit of a solar cell is shown in Fig. 2 and the corresponding current-voltage relation in Eq. 1. The circuit consists of a diode, a current source, a lumped series resistance and a shunt resistance. The current source generates the photocurrent (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 is derived as follows [9]:

$$j(V) = j_{ph} - j_s\left\{\exp\left[\frac{qV + j(V)R_s}{nkT}\right] - 1\right\} - \frac{V + j(V)R_s}{R_{sh}}, \quad (1)$$

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

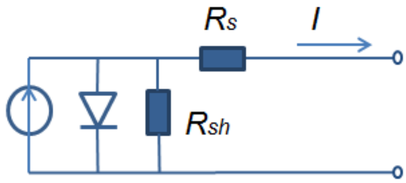

Fig. 2. One-diode model of a solar cell.

3. Results

3.1. Hot Spots

To give an illustrative example, we investigate the effect of a local shunt in a silicon wafer solar cell on its electrical characteristics. These local shunts are often referred to as "hot spots", as under reverse bias large currents can flow through them, locally heating up and damaging a solar module. A local shunt can be introduced into the circuit by reducing the shunt resistance of local elements to certain values. To illustrate the local effect of the shunting, we calculated the local surface potential of the simulated element at the one-sun maximum power point. The result of this calculation is shown in Fig. 3. Figure 3a shows the situation without a local shunt, while Fig. 3b shows the situation when a local shunt between two adjacent fingers is introduced into the circuit. The shunt area is 0.82 mm^2. Figure 3c shows the situation when a local shunt near a finger is introduced into the circuit, and the shunt area is the same as in Fig. 3b. For Fig. 3d, the shunt position is the same as the shunt position of Fig. 3b, however, the shunt area is two times that of the shunt area of Fig. 3b. It can be observed from the figures that at the shunted unit element, the local surface potential is significantly reduced (blue area). However, the effect does not only occur for the shunted element; surrounding circuit elements are also affected. Comparing Fig. 3b with Fig. 3c, the affected area between two adjacent fingers is larger than the affected area near a finger. The reason for this is as follows: Since a solar cell can be regarded as a combination of many unit cells, the potential difference between the shunted area and non-shunted area depends on the voltage drop through the unit cells. The current density in the area near the finger is larger than the current density in the area between two adjacent fingers. As a result, the shunt will draw more current if it is near a finger. With more current flowing through the shunt, the voltage drop through the unit cell is larger, which is closer to the non-shunted elements. Comparison between Fig. 3b and Fig. 3d shows that larger shunt area results in a larger drop in surface potential. The reason is that as the shunt area increases, the current density flowing through the shunt decreases, which results in a lower voltage drop through the unit cell and a larger potential drop.

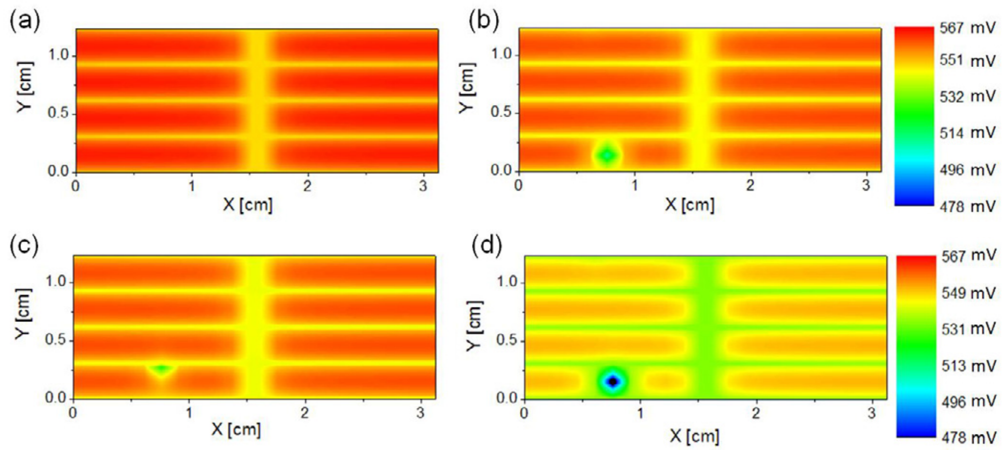

Fig. 3. Surface potential at maximum power point on the simulated solar cell area for a solar cell without shunt (a), with a 0.82 mm^2 local shunt between two adjacent fingers (b), with a 0.82 mm^2 local shunt near a finger (c) and with a 1.64 mm^2 local shunt between two adjacent fingers (d). The shunting resistance for the shunted element was R_{Sh} = 0.82 Ωcm².

To investigate the effect of local shunt on the entire simulated area, we also simulated the current-voltage characteristics. As examples, the current-voltage characteristics obtained for the situations shown in Figs. 3a and 3b are shown in Fig. 4. As can be seen in Fig. 4 the shunt affects mainly the fill factor: the fill factor is reduced from 81.3% to 78.7% when there is a local shunt. The open-circuit voltage V_{OC} and the short-circuit current density j_{SC} are only marginally affected. The efficiency is reduced accordingly by 3.2% relative. Using the one-diode equation, the effective shunt resistance for the entire cell can be calculated. For the given example, the effective shunt resistance for the non-shunted cell is R_{Sh} = 10^5 Ωcm², while it reduces to R_{Sh} = 423 Ωcm² for the shunted cell.

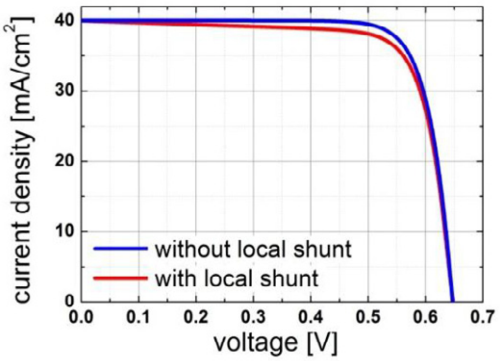

Fig. 4. Simulated current-voltage characteristics for the two circuits shown in Figs. 1(a) and 1(b). j_{sc} in both cases was fixed at 40 mA/cm². V_{oc} of the cell without local shunt is 0.648 V, while V_{oc} of the cell with local shunt is 0.647 V. The fill factor of the non-shunted cell is 81.3%, while the shunt reduces it to 78.7%. The open-circuit voltage is only marginally affected. The relative change in fill factor and efficiency is 3.2%.

3.2. Broken fingers

A broken finger can be introduced into the circuit by setting the resistance of the front metallisation at certain positions to infinity. To illustrate the local effect of a broken finger, we calculated the local surface potential of the simulated element at the one-sun maximum power point. The result of this calculation is shown in Fig. 5. Figure 5a shows the situation without a broken finger, while Fig. 5b shows the situation where one of the fingers is broken. It can be observed from the figures that the broken finger results in an increase of local potential in the surrounding area. This is because the current generated at the broken finger area has to flow a longer distance than before to be extracted by the finger. This leads to an increment of the local effective series resistance. Thus a higher driving force is needed to extract the current generated at the broken finger area, and the local potential increases.

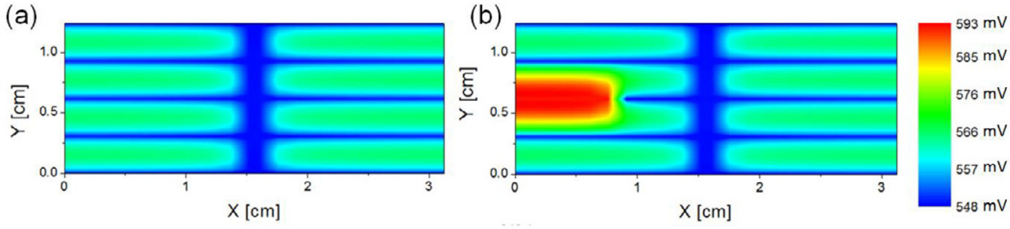

Fig. 5. The simulated voltage distribution of a part of a solar cell at the 1-sun maximum power point: (a) is a cell without a broken finger; (b) is a cell with a broken finger. It can be observed that the broken finger results in an increase of the local voltage.

To investigate the effect of a broken finger on the entire simulated area, we also simulated the current-voltage characteristics. The *I-V* characteristics are shown in Fig. 6. Again, the fill factor was the parameter that was affected most strongly. The fill factor was reduced from 81.3% to 80.4% when a finger was broken. The efficiency was reduced accordingly by 1.1% relative. However, unlike the reason for the shunt problem, the decrease of fill factor here was because of the increase of the effective series resistance. Using the one-diode equation, the effective series resistance for the entire cell could be calculated. For the given example, the effective shunt resistance for the cell without broken finger was $R_S = 0.42\ \Omega cm^2$, while it increased to $R_S = 0.6\ \Omega cm^2$ for the cell with a broken finger. The location of the broken finger also has an influence on the cell performance. A broken finger with breakage located near a busbar introduces a higher decrease of fill factor than a broken finger with breakage located in the centre between two busbars. This is because, if the finger breaks near a busbar, a larger part of the cell will be influenced. One point that needs to be mentioned is that in this simulation, we only investigate a mini-cell with area of 3.58 cm^2. For a full-size solar cell, since its area is much larger, a broken finger will have a smaller impact on the overall cell characteristics.

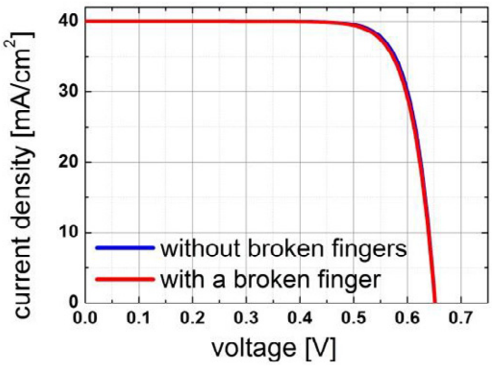

Fig. 6. Simulated current-voltage characteristics for the two circuits shown in Figs. 5(a) and 5(b). jsc in both cases was fixed at 40 mA/cm^2. V_{oc} obtained in both cases was 0.648 V. The fill factor of the cell without a broken finger is 81.3%, while the broken finger reduced it to 80.4%. The relative change in fill factor and efficiency was 1.1% relative.

4. Conclusion and outlook

In this paper, a distributed circuit model that can help investigate local inhomogeneities of silicon solar cells was introduced. The voltage distribution for a solar cell with local inhomogeneities (local shunt and broken finger) was obtained and analysed, and the corresponding *I-V* characteristics were also simulated. It is observed that local inhomogeneity effects have several kinds of influence on the performance of the simulated solar cell. First, the voltage distribution changes in presence of a local shunt or a broken finger. This is due to a change of driving force required to drive out the charge carriers. In both cases, the global *I-V* characteristics are influenced, which is mainly reflected in a change of fill factor. The change of fill factor is mainly due to the change of the effective shunt (hot spot) or the series (broken finger) resistance. In our simulation, a local shunt resulted in a decrease in fill factor of the simulated solar cell by about 3.2% relative. A broken finger resulted in an increase of the global series resistance, and as a result the fill factor of the simulated solar cell with a broken finger decreased by 1.1% relative. It needs to be mentioned that the solar cell simulated in this work has a reduced cell area of 4.5 cm^2. The effect of the entire solar cell can be investigated by connecting sub-cells with the corresponding characteristics in parallel.

Circuit modelling is effective in modelling large-scale local inhomogeneity effects of solar cells. Thus, circuit modelling can be used to overcome the limitations of programmes like Sentaurus TCAD and PC1D in terms of simulated cell area. The calculation time to obtain the whole I-V curve of the simulated cell area was less than one hour, which shows the potential of circuit simulations for even larger-scale effects. In a next step we will combine circuit modelling with characterisation techniques like luminescence imaging. We will also investigate the influence of local inhomogeneities both experimentally and theoretically. From this combination we aim at a better understanding of large-scale transport effects and power losses in Si wafer solar cells, particularly when they are part of a module.

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