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Series spreading resistance in single- and multi-junction concentrator solar cells

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Abstract. The series resistance of concentrator solar cells is determined by the processes of current spreading under the contact grid. The influence of the number of subcells in multi-junction solar cells on these processes is considered in the paper. Using the tube model of current spreading, it is shown that with the increase in the number of subcells, the current distribution of tubes becomes more uniform. This affects the shape of the IV-curve of the spreading resistance in such a way that the magnitude of the resistive losses at the maximum power point decreases.

1. Introduction

The properties of series resistance significantly affect the maximum efficiency of the concentrator solar cell (SC). These properties are determined by the processes of current spreading under the contact grid. Previously, to describe the regularities of current spreading, a tube model was developed [1]. The model described current spreading with the help of a large number of (50 or more) parallel-connected branches consisting of series-connected unequal resistances, and identical p-n junctions. The resistive part of the model is specified by two parameters: \( R_L \) – lateral resistance and \( R_V \) - vertical resistance. In [1] it is shown that the model allows calculating the distribution of currents in tubes and obtaining an IV curve of resistive losses (spreading resistance IV-curve). In this paper, the model was used to study the changes in the process of current spreading in the solar cell with an increase of the subcells number.

In the paper, the existing tube model was extended to multi-junction (MJ) SCs case and the influence of the number of subcells on the spread resistance IV-curve was determined. The extended tube model showed that the number of subcells affects the shape of the spreading resistance IV-curve. At the same time, in the current region near the maximum power point, the resistive losses decrease with increasing of the subcells number. This, as shown, leads to decrease in the lumped linear equivalent of the series resistance \( R_s \).

2. Tube model of current spreading

To study the current spreading in the MJ SC, we used the tube model developed previously [1]. The approach, based on the representation of current lines (correspondingly, on current tubes [2]) is used to describe the resistance. If one presents the current flow through the structure by current lines, the latter will follow along the model paths (Fig.1). In this case, the path of charge carriers in the longitudinal direction is much longer than that in the transverse one (the ratio of the light-sensitive surface area to the shaded by the contact grid one is \( \gg 1 \)). The total resistance on this portion will be mainly determined by the longitudinal propagation (spreading) of charge carriers.
The SC is represented as consisted of two regions: spreading region which has $h_s$ height and vertical one with $h_v$ height (Fig. 1). Each current tube consists of 4 portions: 1 - vertical portion of height $h_1$ in the current spreading region under the face contact, 2 - horizontal portion of length $l_2$ in the current spreading region, 3 - vertical portion of height $h_3$ in the current spreading region and 4 - vertical portion of height $h_4$. Both current spreading resistivity and vertical resistivity we denote to be $\rho_S$ and $\rho_V$ correspondingly. In considering the current tubes to be thin, their thickness on the vertical portions can be written in a form of a coordinate increment along the X axis:

$$dx_1 = \frac{W_1 - dz}{h_s}, \quad dx_2 = \frac{W_2 - dz}{h_2}.$$ 

Correspondingly, the horizontal portion length is given by

$$l_2 = dx_3 = dx_4 = \frac{W_{0.5} - W_z}{h_2}.$$ 

Thickness of any transverse tube $dz$ can be expressed through the amount of current tubes $n$: 

$$dz = \frac{h_i}{n}.$$ 

The number of a current tube (index $i = 1 \ldots n$) can be described in the following way:

$$i = \frac{z}{dz}.$$ 

According to [1], applying above mentioned inputs and the scheme of the SC (Fig. 2) results in the following analytical formula of the $i$-tube resistance:

$$R_i = R_V \cdot n + R_L \cdot i$$

(1)

where: $R_V \approx \rho_V h_v$ and $R_L \approx \frac{\rho_S W_{0.5}^2}{h_s}$.

Note that $R_V$ is mostly determined by the resistance of the substrate due to the large substrate thickness $h_{sub} \approx h_v$. Therefore, $R_V \approx \rho_{sub} h_{sub}$, where $\rho_{sub}$ is the resistivity of the substrate. So $R_V$ can be found from the substrate specifications. The formula for $R_L$ has a form of sheet resistance and can be measured by the multimeter.

Figure 1. The tube model for current spreading in a SC. The SC is presented in a form of several regions: 1, 2, 3 are regions, in which current spreading takes place. Shaded area represents output metallic contacts.

According to the tube model, the equivalent circuit of SC is constructed from parallel branches (Fig. 2) with different resistances. The resistances of $i$-branch can be calculated by Eq. (1). All
branches have a number of similar diodes. Note that series-connected diodes can be replaced, as shown in [1], by one diode with the resulting ideality factor ($A$) and saturation current ($J_0$) obtained by following formulas:

$$
A = \sum_{i=1}^{n} A_i \\
J_0 = \sqrt[n]{\prod_{i=1}^{n} J_{0i}^{A_i}}
$$

The IV curves of the branches can be obtained by solving simple mono-exponential equation:

$$
J_s = J_0 \left[ \exp \left( \frac{q(V-J_s \cdot R_s)}{AKT} \right) - 1 \right]
$$

Figure 2. The distributed equivalent circuit of solar cells used in tube model.

Thus, the application of Eq. (3) together with Eq. (2) and Eq. (1) allows calculating the distribution of currents in the branches of an equivalent circuit (Fig. 2) and obtaining its IV-curve. Repeating the calculation for the case when all the resistances in the equivalent circuit are equal - zero ($R_s = 0$) one can get a resistive-less IV-curve. The difference between such characteristics gives the required for the study IV-curve of the spreading resistance.

3. Calculation of the current spreading processes in MJ SC
The purpose of the calculation was to consider the influence of the number of p-n junctions ($N_{pn}$) in the MJ SC on the resistive losses. For this purpose, according to the tube model described in Section 2, a calculation of the IV-curves for MJ SC with different (from 1 to 8) number of p-n junctions was carried out. The number of current tubes in calculations was 50. In the calculations, the photogenerated current $J_g$ was constant and equal to 7 A/cm². Basically, the results of the calculation do not depend on the choice of this parameter, so we chose the value of $J_g$ at which the maximum efficiency of triple-junction GaInP/GaAs/Ge SC was achieved [2]. Note that $J_0$ was also constant in all calculations and equal to $J_0 = 1 \cdot 10^{-20}$ A/cm². This was made due to the fact that $J_0$ is obtained as a
geometric average (see eq. 2) of the saturation currents of all subcells. It is approximately constant because with an increase in the number of subcells, the average value of the forbidden bandgaps is approximately a constant [3, 4].

In the calculations of resistive losses, the values of $R_L$ and $R_V$ were fixed. The values $R_L = 2.6 \times 10^{-2}$ Ohm·cm$^2$ and $R_V = 0.4 \times 10^{-4}$ Ohm·cm$^2$ were obtained from the analysis of experimental data for GaInP/GaAs/Ge SC [5]. Basically, the results of calculations do not change with other parameters $R_L$ and $R_V$. Partially this is demonstrated in Figure 6.

4. Result and discussion

Figure 3 shows the distribution of current through tubes for SCs with a different number of subcells. It is seen that with the $N_{pn}$ increase, the distribution becomes more uniform. This may be due to the fact that as the number of subcells increases, the role of the series resistance decreases in comparison with the resistance of the diodes. The change in the distribution of currents across the tubes affects the resistive losses. The IV-curves of the spreading resistance is shown in Fig. 4. It is seen that the shape of the curve changes, and there are regions in which the spreading resistance increases with an increase in the number of pn-junctions (approximately from 0 to 5 A/cm$^2$ in Fig. 4) and vice versa decrease (from 5 to 7 A / cm$^2$). The second region is of practical interest since it contains the maximum power point (MPP).

![Figure 3. Current distribution in tubes for SCs with a different number of subcells.](image)

![Figure 4. IV-curves of the spreading resistance for SCs with a different number of subcells.](image)

To study the reduction of resistive losses at the MPP, the lumped resistance at the point was used. This resistance was calculated as the ratio of the spreading resistance value at the point to the its current. Note that due to the fact that such resistance connected with MPP it is value considered to be a lumped linear resistance equivalent ($R_s$). Such equivalent is widely used in photovoltaics because it allows describing the SC IV-curve in practically important cases (up to the maximum of efficiency) without taking into account the distributed character of the spreading resistance [2, 6]. Dependence of $R_s$ on the number of subcells is shown in Figure 5. It is evident that this resistance decreases with the $N_{pn}$ increasing. Thus, a change in the current distribution in the tubes of the SC (Fig. 3) reduces the resistive losses at the operating point, which effectively reduces the linear lumped resistive equivalent $R_s$.

In addition, the calculation of the influence of the spreading resistance parameters ($R_L$ and $R_V$) on the value of the $R_s$ was carried out. The parameters $R_L$ and $R_V$ were varied by deviation from the standard ones. The result of the calculation is shown in Figure 6. It can be seen that $R_s$ is much more dependent on $R_L$ than on $R_V$. At the same time, the general form of the regularity (the decrease of $R_s$ with $N_{pn}$ increasing) is preserved. Also the tendency toward saturation is observed with an increase in the number of subcells.
Figure 5. Lumped series resistance of SCs with a different number of subcells.

Figure 6. The influence of spreading resistance parameters ($R_L$ and $R_V$) on the dependence of lumped series resistance of SCs with a different number of subcells.

5. Conclusion

In the paper, a tube model is used to describe the process of current spreading under the contact grid of solar cells with any structure including MJ SCs. It has been calculated that the increase of the subcells number in MJ SC affects the process of current spreading. The distribution of currents in tubes with increasing number of subcells becomes more uniform. It is assumed that this may be occurs due to the fact that the role of the series resistance decreases in comparison with the resistance of diodes.

As a consequence of the change in the tube currents distribution, the IV-curve of the spreading resistance changes. In the region around the maximum power point current, the spreading resistance decreases with increasing number of subcells. Calculation of the linear lumped equivalent (of the series resistance) $R_s$ has shown that $R_s$ decreases with an increasing number of subcells. It was also shown that $R_s$ critically depends on the lateral resistance $R_L$.

Thus a change in the current distribution in the tubes of the SC with increasing of its subcells number reduces the resistive losses at the maximum power point, which effectively reduces the lumped resistive equivalent $R_s$.

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