DISTRIBUTED RESISTANCE EFFECTS SIMULATION IN CONCENTRATOR MJ SCS USING 3D-NETWORK MODEL

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ABSTRACT: A new 3D model for estimating influence of the effects associated with the distributing character of internal resistances in multijunction solar cells has been elaborated. In the model, a cell is divided by area into some number of units, each photoactive junction of which is described by an equivalent circuit consisting of the current source, series resistance, shunting resistance and three diodes with different ideality factors. Two diodes connected with the current source in the forward polarity simulate the injection and recombination mechanisms of the current flow. Including the third diode connected to the circuit in the opposite direction, which simulates the reverse branch of the subcell dark J-V characteristic, allows simulating more correctly the J-V characteristic of multijunction solar cells at their operation in the conditions of the spatial and spectral redistribution of the illumination created by sunlight concentrators due to the chromatic aberration. The J-V characteristic of a GaInP/GaInAs/Ge solar cell under 500X Fresnel lens concentrator has been calculated. Influence of the shape of the reverse branch of the GaInAs subcell dark J-V characteristic and the photoeffect in the tunnel diode on the J-V characteristic of a multijunction solar cell have been estimated. Dependencies of the open-circuit voltage, the fill factor and the efficiency on the concentration ratio for a GaInP/GaInAs/Ge cell have been simulated and compared with measured ones. It has been shown that the 3D model provides the much better accuracy than the non-distributed circuit does: the optimal number of units to divide a multijunction solar cell on ensuring the necessary calculation accuracy has been estimated.
Keywords: concentrator cells, multijunction solar cell, simulation

1 INTRODUCTION

Photovoltaic installations with sunlight concentrators and multijunction solar cells (MJ SCs) are among the most intensively being developed directions in solar power engineering.

SC operation conditions in such systems are characterized by high values of the radiation flux density incident on the cell surface, by nonuniform illumination of the cell area and by spectral redistribution of radiation due to the chromatic aberration in Fresnel lens (FL) sunlight concentrators. These effects result in manifestation of nonlinear effects of the cell series resistance and in the dependence of the SC efficiency on the illumination distribution, which may finally lead to reduction of the SC efficiency [1–3]. Evaluation of the given effects in simulating the SC characteristics can be done by including fictitious nonlinear resistance into the equivalent circuit [4] or by constructing distributed equivalent circuits [5-11]. The second approach describing real physical processes in the cell is more acceptable.

The distributed equivalent circuits may be of two versions: linear [5-8] and 3D models [9-11]. The linear models are much easier for calculations, but they are not adequate to the physical reality in cases, when the illumination distribution on the cell surface is nonuniform or the cell contact grid has no linear symmetry. The 3D models are more appropriate for calculations and may be used for describing contact grids of all patterns at any illumination distributions.

The goal of the present work is the elaboration of the distributed 3D model for GaInP/GaInAs/Ge MJ SCs, which is valid for accurate estimating the influence of the effects associated with the distributed character of the internal resistance of SCs and chromatic aberration in concentrator optics.

2 EQUIVALENT CIRCUIT OF CONCENTRATOR GaInP/GaInAs/Ge SCs

2.1 Concentrator and cell designs

The high photoconverter efficiency and the cheap material of the optical concentrator make the investigations intended for creating photovoltaic modules based on GaInP/GaInAs/Ge SCs and Fresnel lenses of polymer materials to be actual [12-19].

In the work, the simulation was carried out for the pair "FL with silicon-on-glass structure – GaInP/GaInAs/Ge triple-junction SC 4x4 mm^2 in size". The Fresnel lens had a squared form and ensured the average concentration ratio of 100X for the area of 4x4 mm^2 at the optical efficiency of about 90% and of 500X for the area of the area of 2x2 mm^2 at the optical efficiency of about 85%. The lens design was optimized by the method described in [20]. The investigated cell structure is presented in Fig. 1. The photocurrent matching of the subcells was done for the terrestrial AM1.5D (cell SC1) and space AM0 solar spectra (cell SC2). The contact grids of the cells were one-dimensional regular grids with a pitch of 55 μm for the SC1 and 200 μm for the SC2 at the contact finger width of 6.5 μm.

Simulated distributions of photocurrents for the three subcells of the SC1 are presented in Fig. 2. The chromatic aberration in the FL results in spectral redistribution of radiation on the surface of the SC1. Since different subcells of the MJSC absorb the sunlight of different spectral ranges, the spectral redistribution results in mismatch of photocurrent densities for the subcells across the cell's surface. This effect is extremely valuable for the Ge-subcell in comparison with GaInP and GaInAs subcells.

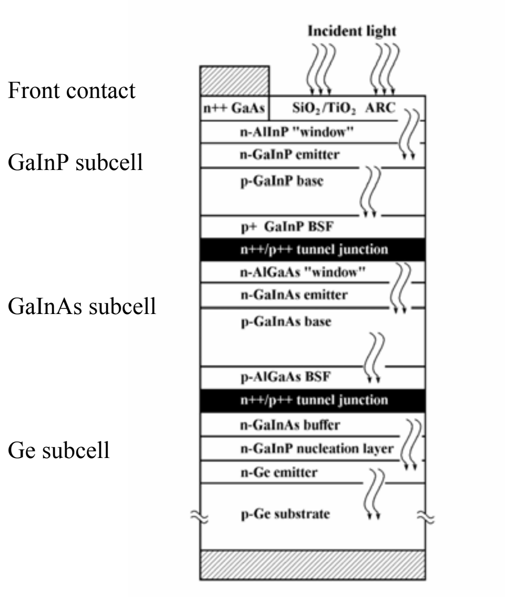


Figure 1: Structure of the investigated GaInP/GaInAs/Ge SC

Table 1: Photocurrent densities of the subcells in the SC1 and SC2 multijunction cells

	Photocurrent density, mA/cm^2	
Subcells	SC1 (AM1.5D)	SC2 (AM0)
GaInP	13.44	16.83
GaInAs	12.46	16.62
Ge	20.10	24.12

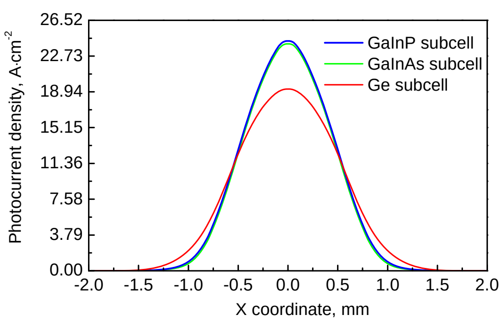


Figure 2: Rated photocurrent distribution in three subcells of the SC1 under AM1.5D

The mismatch of the generation photocurrent densities of the subcells results in the appearance of the horizontal spreading currents in the structure. The non-continuous top contact causes, in turn, appearance of the spreading current under the grid. The horizontal spreading currents lead to redistribution of the potential and to additional ohmic losses in the heterostructure, which lowers down the SC efficiency. The values of the spreading current densities and power of caused by them losses are determined by thicknesses and doping levels of the heterostructure layers and also by the current of the tunneling p-n junctions. It has been shown experimentally that in some cases these losses may lead to the absolute reduction of the multijunction SC efficiency by 6,5%[1].

2.2 3D-network model

To account for the horizontal spreading currents and the effect associated with them, a three-dimensional distributed equivalent circuit has been elaborated. The 3D-network model is a series-parallel connection of elemental units, each of which describes a definite zone of a subcell, tunnel diode or contact grid of the GaInP/GaInAs/Ge SC (see Fig. 3) and is a site of a three-dimentional network. Similar distributed equivalent circuits for singlejunction SCs were proposed in the works [10, 11].

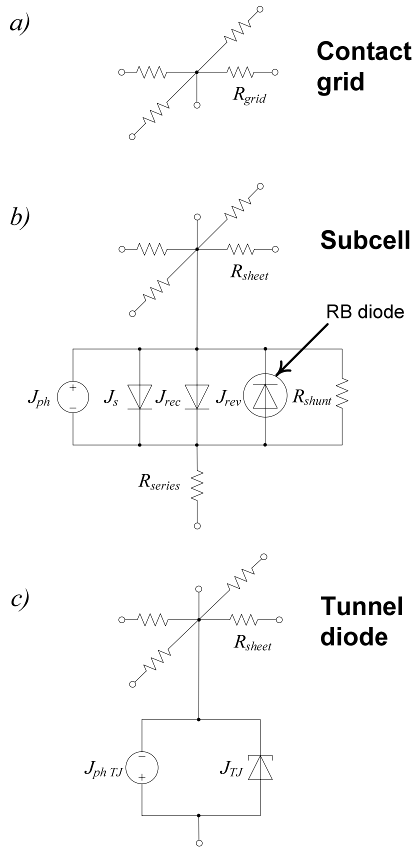


Figure 3: 3D-network model units of a part of the multijunction SC front contact grid (a), subcell (b) and tunnel diode (c).

The J-V characteristic of each p-n junction of a MJ SC subcell is approximated by the following formula:

$$J(V) = J_{ph} - J_S \exp\left(\frac{qV}{kT}\right) - J_{rec}\exp\left(\frac{qV}{2kT}\right) + \\ + J_{rev}\exp\left(-\frac{qV}{A_r kT}\right) - \frac{V}{R_{shunt}}, \quad (1)$$

where J_{ph} is the subcell photocurrent, J_s is the bias current density, J_{rec} is the recombination current density, $J_{rev} = J_s + J_{res}$ is the current density of the reverse branch of the J-V curve of the subcell, A_r is the reverse branch non-ideality factor, q is the electron charge, k is the Boltzmann constant, T is temperature, R_{shunt} is the shunting resistance.

The tunnel diode J-V characteristic is described through its photocurrent $J_{ph\,TJ}$ and dark J-V characteristic $J_{TJ}(V)$:

$$J(V) = J_{TJ}(V) - J_{ph\,TJ}. \tag{2}$$

In the equivalent circuit, a separate photoactive junction of a MJ SC in a unit is connected in series via resistance R_{series} with other photoactive junctions in the unit. With the help of sheet resistances R_{sheet}, the interconnections between units within a subcell are simulated. For external connection to contact grids, the contact resistance $R_{contact}$ is used. Interconnections between units and to the external circuit via the contact grid are simulated through the grid resistances R_{grid}. If there is no grid in the considered direction, R_{grid} is set to be respectively large.

The merit of the elaborated model compared with those presented in [5-11] is independent allowance for all parts of MJ SC structure, incorporation a diode into the subcell equivalent circuit, description the reverse branch of the J-V curve of a subcell (reverse branch diode or RB diode), and allowance for the photocurrent generated in the tunnel diode. The shape of the subcell J-V characteristic reverse branch may affect essentially the J-V characteristic of a MJSC at a photocurrent mismatch of its subcells. Note that this effect cannot be allowed for by means of a shunting resistance. The photoeffect in the tunnel diode may play a noticeable role at high radiation concentration ratios and an imperfect tunneling junction and lead to reduction of the J-V characteristic open circuit voltage and the fill factor [21].

For calculating the J-V characteristic of the given distributed circuit, a program was implemented, which allows simulating 3D-networks with up to 1000x1000 units.

2.3 Simulated J-V characteristics of the GaInP/GaInAs/Ge SC under lens concentrator illumination

By means of the elaborated model, the current-voltage characteristics for the SC1 have been calculated. Fig. 4 presents rated J-V characteristics obtained in using the distributed equivalent circuit in the case of uniform illumination of a cell area and the uniform subcells photocurrents' distributions (see Fig. 2), in comparison with the characteristic being obtained for the equivalent circuit with concentrated parameters. It is seen that, at uniform illumination, the J-V characteristics obtained with the help of the 3D-network model and a non-distributed circuit practically coincide.

The effect of the reverse branch (RB) diode in the equivalent circuit of the subcell on the J-V characteristic of a MJSC is illustrated in Fig. 5. It is clear that the multijunction cell current at zero voltage at presence of such a diode with the ideality factor $A_r = 2$ will not be limited by the GaInAs subcell photocurrent. In this case, the current flow through the GaInAs subcell p-n junction in reverse direction caused by the higher photocurrent of the GaInAs subcell p-n junction in reverse direction caused by the higher photocurrent of the GaInAs or Ge subcell will take place.

A similar effect can be obtained, when the shunting resistance in the GaInAs subcell is accepted to be quite small. However, another "parasitic" change will appear on the J-V characteristic – decrease in the current in the maximum power region leading to the decrease in the FF and the cell efficiency. Thus, apparently, it is necessary for correct description of MJSCs to include both RB diodes and a shunting resistance into the equivalent circuits.

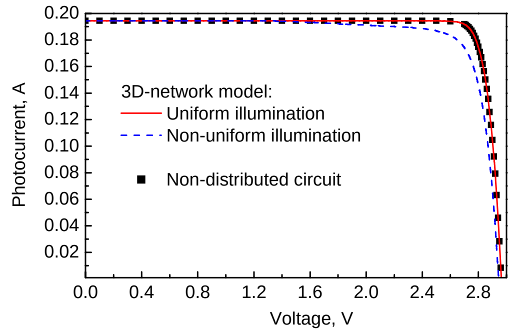


Figure 4: Simulated J-V characteristics of the SC1. For non-uniform illumination the photocurrent distributions considered as presented in Fig. 2.

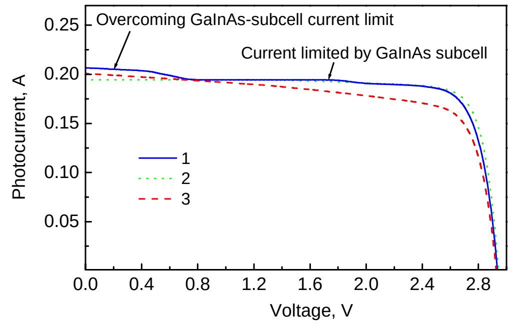


Figure 5: RB diode and shunting resistance effects on simulated J-V characteristics of the SC1 using 3D-network model: 1 – with RB diode, 2 – without RB diode, 3 without RB diode and having shunting resistivity in GaInAs-subcell of 10 $\Omega\cdot cm^{-2}$. The photocurrent distributions considered as presented in Fig. 2.

Accounting for the photoeffect in the tunnel diode (Fig. 6) results in the decrease of the open circuit voltage both in the case of a circuit with concentrated parameters and the case of a distributed equivalent circuit. In the second case, at nonuniform illumination distribution on a SC (see Fig. 2), the voltage decrease in the vicinity of the maximum power point appears to be less noticeable.

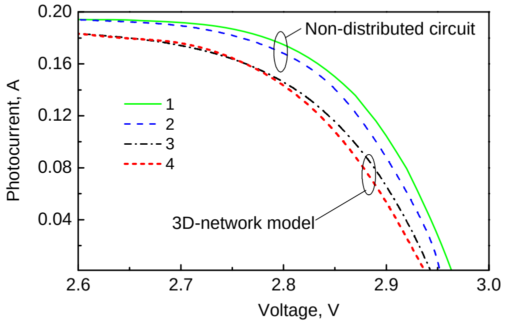


Figure 6: Influence of photoeffect in tunnel diode on the simulated J-V characteristics for the SC1: 1,3 – without photoeffect in tunnel diode; 2,4 – including photoeffect in tunnel diode. The photocurrent distributions considered as presented in Fig. 2.

3 DISTRIBUTED RESISTANCE EFFECTS

3.1 Influence of sheet resistance on the J-V characteristic

The change of the J-V characteristic shape (see Fig. 4) in coming to nonuniform illumination from uniform one is caused by appearance of the horizontal spreading current due to the generation nonunifomity and to losses on the sheet resistances. Fig. 7 presents a set of J-V characteristics for the SC1 in dependence on the values of the sheet resistances (R_{sheet}) between cells. For simplicity all sheet resistances in the model were varied simultaneously.

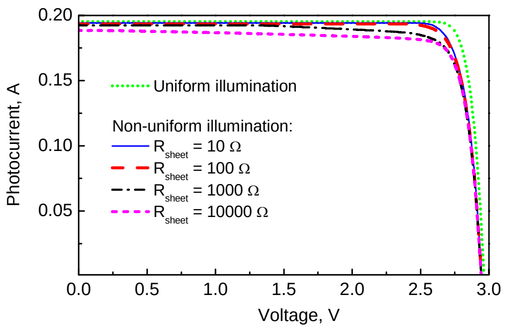
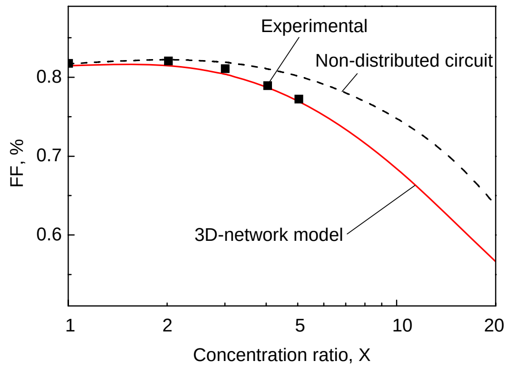


Figure 7: Influence of specific sheet resistance values on J-V characteristics simulated by 3D network model for the SC1. For nonuniform illumination, the photocurrent distributions are considered as presented in Fig. 2.

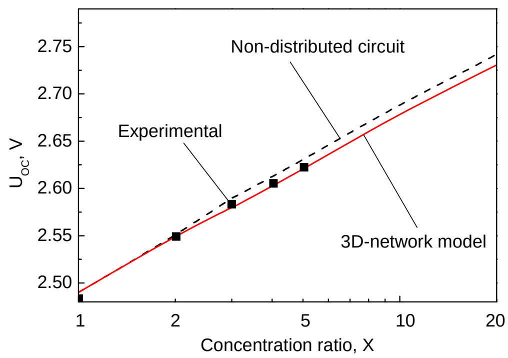
It is seen that losses on the sheet resistances are valuable at $R_{sheet} > 100$ Ohm. Great values of the sheet resistances lead to the decrease of the FF and, hence, of the SC efficiency. At the resistance equal to 10000 Ohm, also short circuit current decreases. At the decrease of the sheet resistance lower than 100 Ohm, the J-V characteristic does not, practically, change its shape, but, however, does not stand to repeat the J-V characteristic of an illuminated cell. This is explained by losses due to current spreading under the contact grid at super high (>1500X) radiation concentration ratios.

3.2 Determination of the optimal number of units for the 3D-network model

Fig. 8 presents rated dependences of the FF and V_{oc} of a J-V characteristic of triple junction GaInP/GaInAs/Ge SC (SC2, see Table 1) efficiency on the out-atmospheric sunlight concentration ratio obtained with the use of the distributed model and one with lumped parameters in comparison with the experimental values. It is seen from Fig. 8 that, in the case of the nonconcentrated sunlight, correct results are obtained in using both models, but at high concentration ratios they differ.



a)



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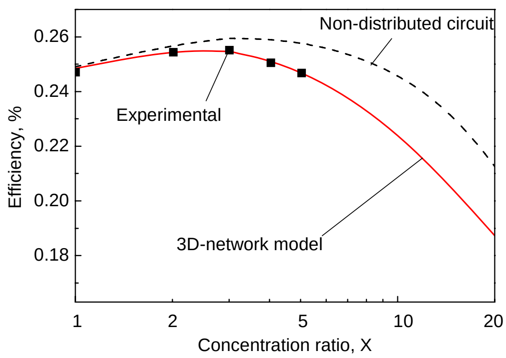

c)

Figure 8: Fill factor (a), open-circuit voltage (b) and efficiency (c) of SC2 versus sunlight concentration ratio.

Accuracy in calculating of the SC J-V characteristic, when the series resistance nonlinear properties and effects associated with the chromatic aberration in the concentrator are manifested, depends on the number of units in the divided SC. If this number of units is deficient, the inaccuracy in J-V characteristic calculation will be great, because the selected circuit can not adequately describe the effects of the current flow in a solar cell. If this number is too great, the calculation difficulty rises extremely without increasing the output data accuracy. For this reason, the choice of the optimum number of units for dividing is an actual problem.

The sufficient number of the units depends on the current load on a cell. Higher the sunlight concentration ratio, and hence the flowing current, greater will be the necessary number of units. The sufficient number of units N_{min} for a zone of a cell associated with any current collection point may be determined by the formula:

$$N_{\min} \approx \sqrt{\frac{J_{out} q R_{sheet}}{kT\delta J_{\max}}}, \qquad (3)$$

where $\delta J_{\max}$ is the maximally permissible error in determining the current, J_{out} is the current flowing through the current collection point.

By the "current collection point" is meant a point from which the current is transferred "up" in the 3D-network. For the top subcell, the determination of the current collection points is obvious – they are the points of the front contacts of a MJSC. The number of points is specified by the contact grid pattern of the cell. In the simplest case it is the number of contacts in the contact grid. For other subcells the number of the current collection points is arbitrarily assigned, since they are connected in the 3D-network with upper subcells through tunnel diodes. Thus, for the top subcell, J_{out} is the current through the contact adjacent to the given region. For the rest subcells, it is the current through the tunneling diode in the given zone.

The results of calculation of the optimum number of units by the formula (3) for the acceptable accuracy in calculating the current of 1 % from the absolute value are presented in Fig. 9. Also, in this figure, the results of simulation were obtained by comparison of the current-voltage characteristics with the use of different dimensionality of models. It is clear that satisfactory fitting of the simulation results to the estimation obtained analytically is ensured.

The dependence presented in Fig. 9 gives the number of units, into which the subcell region adjacent to the current collection point should be divided. The total number of units of a subcell sufficient for describing the effects associated with the current spreading is equal to the sum of the specific numbers of units for all current collection points:

$$N^{\Sigma}_{\min} = \sum_{i=1}^{M} N_{\min i}, \qquad (4)$$

where $N_{min\ i}$ is the sufficient number of units for the ith current collection points, M is the number of current collection points.

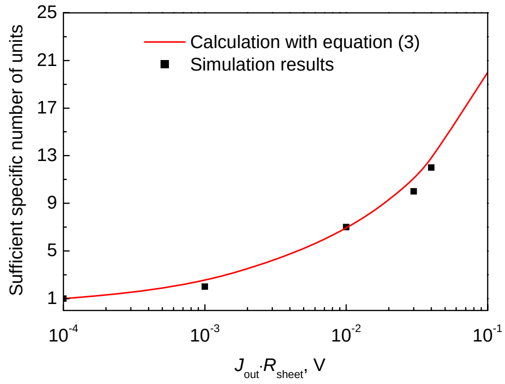

Figure 9: Sufficient specific (on one collector) number of units versus product of the current J_{out} and the sheet resistance R_{sheet} (Ω) for the current calculation accuracy of 1%.

4 SUMMARY

Main results of the work may be formulated as follows:

- A three-dimensional distributed equivalent circuit of a triple junction GaInP/GaInAs/Ge solar cell for allowing for the effect of current spreading in its layers at nonuniform distribution of illumination on a SC has been elaborated;
- With the use of the elaborated model, the J-V characteristics of a GaInP/GaInAs/Ge SC operating in the conditions of uniform and nonuniform illumination concentrated by a lens have been calculated. The effect of the sheet resistance on the shape of the J-V characteristic at spectral redistribution of the concentrated sunlight flux on the SC surface due to the Fresnel lens chromatic aberration has been studied. The effect of the shape of the photoactive p-n junction J-V characteristic reverse branch on the MJSC J-V characteristic in the case of mismatch of photocurrents of its subcells and the photoeffect in the tunnel diodes has been shown;
- Comparison of the lumped and the distributed models at different characteristics of the sunlight flux has been done. It has been shown that the increasing error in calculating the J-V characteristic is proportional to the value of the current load on a SC. The sufficient number of units of a tree-dimensional distributed equivalent circuit in dependence on the current coming to one contact and on the sheet resistance value has been determined.

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