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Modeling the current-voltage characteristics and optimizing the laser-powered photovoltaic converters with a spot-type rear contact

A.D. Malevskaya ✉, **M.A. Mintairov, V.V. Evstropov, D.A. Malevsky, A.V. Malevskaya, S.A. Mintairov, N.A. Kalyuznyy**

Ioffe Institute, St. Petersburg, Russia
✉ anmalevskaya@mail.ioffe.ru

Abstract. A method for comprehensively modeling the current-voltage characteristics of laser-powered photovoltaic converters (PVCs) with spot-type rear contact is proposed. The method accounts for both optical losses caused by shading of the photoactive region and electrical losses caused by radial current spreading to the spot-type rear contacts. A balance between these factors is achieved at specific values of the diameter of spots and distance between contacts, which could be determined using the proposed method. The geometric parameters of the rear contacts (diameter and spot pitch) were optimized to maximize the laser radiation conversion efficiency of the AlGaAs/GaAs PVCs.

Keywords: photovoltaic converters, spot-type contact, current spreading, current-voltage characteristics

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Конференционная статья
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Моделирование вольт-амперных характеристик и оптимизация фотоэлектрических преобразователей лазерного излучения с точечным тыльным контактом

А.Д. Малевская ✉, **М.А. Минтаиров, В.В. Евстропов, Д.А. Малевский, А.В. Малевская, С.А. Минтаиров, Н.А. Калюжный**

Физико-технический институт им. А.Ф. Иоффе РАН, Санкт-Петербург, Россия
✉ anmalevskaya@mail.ioffe.ru

Аннотация. В работе предложена методика комплексного моделирования вольт-амперных характеристик фотоэлектрических преобразователей (ФЭП) лазерного излучения с точечным тыльным контактом. Методика позволяет учесть как оптические потери, связанные с затенением фотоактивной области, так и электрические потери, обусловленные радиальным растеканием тока к тыльным точечным контактам. Баланс между этими факторами достигается при определённых значениях диаметра и расстояния между контактами, которые могут быть определены с помощью предложенного метода. Проведена оптимизация геометрических параметров тыльных точечных контактов (диаметр и шаг) с целью максимизации эффективности преобразования AlGaAs/GaAs ФЭП.

Ключевые слова: фотоэлектрические преобразователи, точечный тыльный контакт, растекание тока, вольт-амперные характеристики

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Introduction

The development of highly efficient photovoltaic converters (PVCs) for laser radiation (LR) requires finding a compromise between minimizing optical losses and reducing electrical contact resistance [1 – 4]. In conventional PVCs and solar cells, only the front contact design requires optimization with this viewpoint. However, PVCs with record-breaking conversion efficiencies for monochromatic radiation [5] as well as high-power (200–500 W/cm^2) laser radiation [6] with $\lambda = 800$–850 nm were developed recently. In such PVCs the epitaxial AlGaAs/GaAs heterostructure is separated from the growth-wafer and transferred to a carrier-substrate with a metal reflector on its surface. The embedded rear metal reflector offers several advantages to the PVC. The reflector returns recombination radiation to the active region and allows decreasing the thickness of the absorber materials without loss of charge carrier collection that leads to high conversion efficiency. However, such a PVC design also requires optimizing optical and resistive losses for the rear contact.

A promising geometry for this purpose is the use of spot-type rear contact, which is effectively used in the light-emitting diodes produced by lift-off techniques [7]. However, the spot-type contact caused an increase in series resistance associated with the radial spreading of current to the spots. Today, there are no universal methods for taking into account both optical and electrical losses for quantitatively estimating the influence of spot-type contact geometry on the current-voltage characteristics (*I–V* curves) of the PVC.

The aim of the work is to develop a method that combines the calculation of optical and electrical parameters for creating the optimal design for a spot-type rear contact. The method is based on two- [8] and three-parameter [9] tube models, which was successfully used to analyze solar cells with a solid rear contact and a finger-pitched front contact construction.

Materials and Methods

The proposed method for modeling a solar cell with a spot-type rear contact consists of several sequential stages. The first stage is the evaluation of the optical parameters. Replacing a solid rear contact with a spot-type contact affects the PVC's spectral sensitivity and saturation current. The changes in these parameters are calculated using linear interpolation between experimental data obtained for samples with different spot-type rear configuration.

Based on the adjusted parameters, such as spectral sensitivity, photogenerated current, dark saturation currents, the generation part of *I–V* curve is calculated. Such *I–V* curve describes the behavior of the *p–n* junction without taking into account ohmic losses according to equation (1):

$$J = J_g - \sum \left[J_{0,j} \exp\left(\frac{qV}{A_j kT} \right) - 1 \right], \tag{1}$$

Next, the losses on the front contact grid are taken into account using the method described in [9], in which a distributed equivalent circuit describing the part of the structure from the upper layer to the emitter is considered. The *I–V* curve of the PVC taking into account the resistance of top part PVC (from top contact-layer to the emitter) is calculated by using equation (2):

$$J = J_g - \sum \left[J_{0,tr,j} \exp\left(\frac{q\left[V - j \cdot R\right]}{A_j kT} \right) \right], \tag{2}$$

where J is the current density, J_g is the photogenerated current, V is the applied voltage, k is the Boltzmann constant, T is the temperature, q is the electron charge, $J_{0,tr,j}$ is the saturation currents for current tubes, R is the resistance.

This *I–V* curve is used to calculate the *I–V* curve which takes into account current spreading to the spot-type rear contacts. The equation was arrived assuming that the lower part of the *I–V* curve structure (from rear contact-layer to the base layer) could be divided into repeating triangular fragments between the contacts (Fig. 1). Each fragment is divided into m parts, in which the current flows along n parallel current tubes. The resistance of the i-th current tube in the jth part is calculated (as in [9]) by equation (3):

$$R = R_V \cdot n + R_L \cdot i, \tag{3}$$

where R_V is the vertical resistance is usually determined by the properties of the substrate material on which the PC epitaxial structure is grown, $R_{L_{i,j}} = \left[\left(\frac{D}{2} \right)^2 + \left(\frac{D}{2} \cdot j \right)^2 \right] \cdot \frac{R_{sheet}}{w}$ is the lateral resistance depends on the tube number, $w = D/4m$ is the tube thickness, D is the distance between contacts, R_{sheet} is the sheet resistance. The equation for $R_{L_{i,j}}$ is obtained by analogy with the calculations given in [8]. The *I–V* curve calculation can be performed using a similar procedure proposed in [9]: the number of parts $\boldsymbol{m}$ and the number of tubes $\boldsymbol{n}$ are selected, the resistances R_V and R_L, are calculated, and the resistances of the tubes $R_{i,j}$, are determined, then the *I–V* curve for the all current tubes are calculated. Summation of the all the tube *I–V* curves allow obtaining the complete PVC *I–V* curve.

The model discussed above was applied to search for the optimal parameters of the spot-type rear contacts of AlGaAs/GaAs PVC. The epitaxial heterostructure (Fig. 2) of PVC was grown by the metal-organic vapor phase epitaxy.

To study the influence of contact grid parameters on resistive losses, three PVC samples based on the epitaxial heterostructure (Fig. 2) were fabricated and studied. The only variable parameter were the finger pitches of the front contact: 140 μm (sample A), 180 μm (sample B), and 220 μm (sample C). The spot-type rear of all samples were the same with $d = 10$ μm and $D = 75$ μm.

To demonstrate the contribution of each modeling step, Fig. 3 shows the *I–V* curves for sample A, obtained taking into account various components of ohmic losses. The initial *I–V* curve (curve 1, blue line) is calculated based on experimental *I–V* curve without taking into account resistive losses by Eq. (1). At the next step of the model procedure, the resistive losses caused by spreading between the fingers of the front contact are taken into account (curve 2, orange line) according to Eq. (2). The radial spreading of current between the spot-type rear contacts further increases the resistive losses. The final simulated *I–V* curve (curve 3, green line) demonstrates good agreement with the experimental data (curve 4, red dots) and allows determining the parameters of PVCs (Table 1).

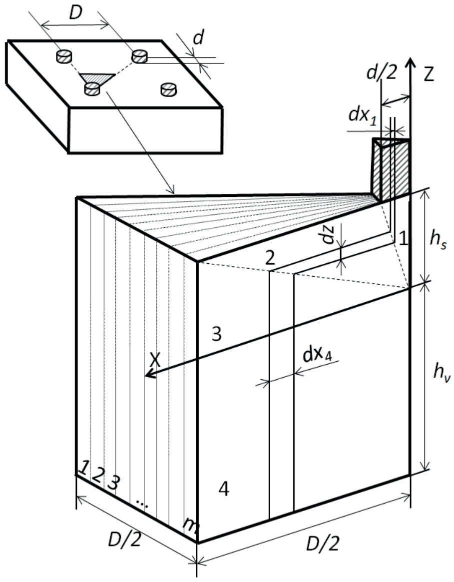

Fig. 1. Schematic representation of the model of radial current spreading in lower part of PVC with the spot-type rear contacts

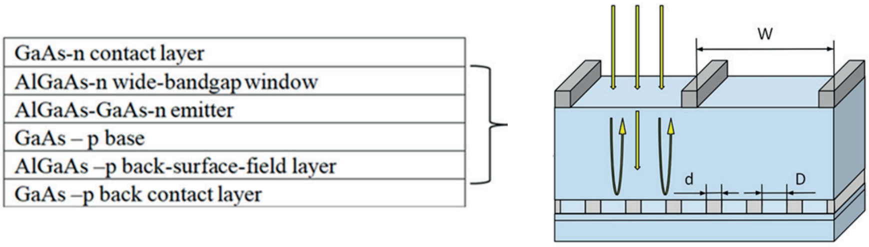

Fig. 2. Schematic representation of the AlGaAs/GaAs PVC epitaxial heterostructure

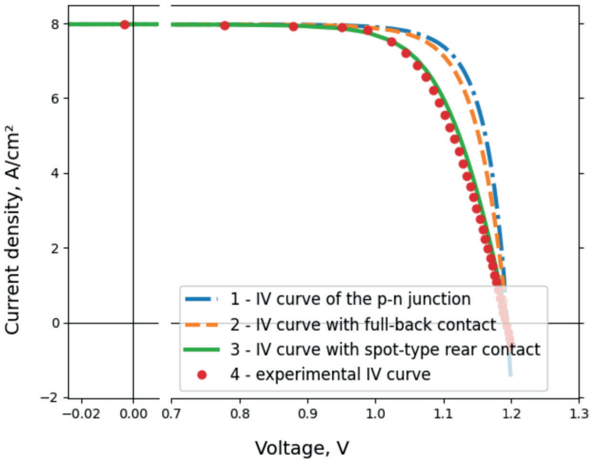

Fig. 3. *I–V* curve of PVC at various stages of modeling: 1 corresponds to the non-resistive *I–V* curve of the *p–n* junction, 2 to the *I–V* curve taking into account losses on the front contact grid, 3 to the *I–V* curve with additional consideration of current spreading to spot-type rear contacts, 4 to the experimental *I–V* curve

Table 1

Parameters of contact grid templates and modeling parameters

	Sample A $W = 140$ µm	Sample B $W = 180$ µm	Sample C $W = 220$ µm
J_{01}, A/cm^2	$4.42 \cdot 10^{-20}$	$5.88 \cdot 10^{-20}$	$5.41 \cdot 10^{-20}$
J_{02}, A/cm^2	$2.63 \cdot 10^{-10}$	$2.46 \cdot 10^{-10}$	$2.64 \cdot 10^{-10}$
finger-pitched front contact			
R_{Sheet},Ohm·cm^2	11.93	12.03	11.96
R_V, Ohm·cm^2	0.0		
ρ_{Me}, Ohm·mm^2/cm	$1.6 \cdot 10^{-6}$		
spot-type rear contacts			
R_{Sheet},Ohm·cm^2	11.98	12.00	11.99

Notations. W is the pitch of the front contact fingers, J_{01} and J_{02} are the saturation currents with ideality factors $A = 1$ and $A = 2$, RV is the vertical resistance of the structure, ρ_{Me} is the specific resistance of the contact finger, R_{Sheet} – sheet resistance.

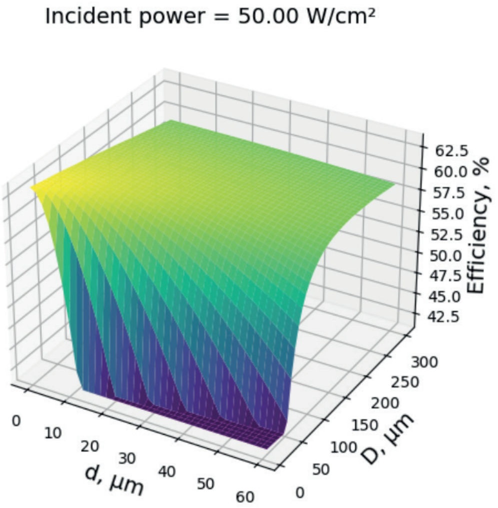

Fig. 4. Dependencies of the efficiency of laser radiation conversion (λ = 800–850 nm) at an incident power of 50 W/cm2 on the spot diameter (*d*) and intercontact distance (*D*) of spot-type rear contact for AlGaAs/GaAs PVC

To optimize the contact geometry, the proposed method is applied to PVC as a number of iterations. A series of calculations is performed for an array of spot-type rear contact diameters and intercontact distance values. For each variant, the conversion efficiency is determined. Analysis of the resulting dependence allows identifying the optimal values that lead to a balance between optical and electrical losses. The method was applied to an AlGaAs/GaAs PVC with an finger pitches of front contact of W = 140 μm. The calculation results are shown in Fig. 4. It was found that the optimal parameters for a high incident power of P_{inc} = 50 W/cm^2 are the following. Obtained parameters allows increasing the efficiency of laser radiation conversion (λ = 800–850 nm) by 1.2% due to the changing intercontact distance D from 75 to 17.4 μm and spot diameter from d = 10 to 2 μm.

Conclusion

A method for comprehensive modeling and optimization of photovoltaic converters with spot-type rear contact was developed, based on a modified tube model. The method allows quantitatively accounting for the competing effects: shading of the back side of the photovoltaic converter by the spot-type contacts and increase in the series resistance due to radial current spreading between spots. An iterative calculation of the photoconversion efficiency for an AlGaAs/GaAs PVC was performed by varying the parameters of the spot-type rear contact. It is shown that the optimal parameters (spot diameter of 2 μm and intercontact distance of 17 μm) allow increasing the efficiency by 1.2% compared to the case of a sample with a spot diameter of 10 μm and an intercontact distance of 60 μm, which exhibited an efficiency of 62.0% [6]. Thus, the proposed method provides a tool for the rear contact design of high-efficiency photovoltaic converters with embedded metal reflectors.

Conflict of interest

The authors declare that they have no conflict of interest.

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THE AUTHORS

MALEVSKAYA Anastasia D.
anmalevskaya@mail.ioffe.ru
ORCID: 0009-0008-5664-6130

MALEVSKAYA Aleksandra V.
amalevskaya@mail.ioffe.ru
ORCID: 0000-0003-4018-6631

MINTAIROV Mikhail M.
mamint@mail.ioffe.ru
ORCID: 0000-0002-3481-477X

MINTAIROV Sergei A.
mamint@mail.ioffe.ru
ORCID: 0000-0002-6176-6291

EVSTROPOV Valery V
vvevstropov@gmail.com
ORCID: 0000-0001-7158-0426

KALYUZNYY Nikolay A.
Nickk@mail.ioffe.ru
ORCID: 0000-0001-8443-4663

MALEVSKY Dmitry A.
dmalevsky@scell.ioffe.ru
ORCID: 0000-0002-9337-4137

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