Semiconductors, 2024, Vol. 58, No. 10

Three-parameter tube model of current spreading in solar cells

© *A.D. Malevskaya, M.A. Mintairov, V.V. Evstropov, D.A. Malevskiy, N.A. Kalyuzhnyy*

Ioffe Institute,
194021 St. Petersburg, Russia
E-mail: anmalevskaya@mail.ioffe.ru

Received May 3, 2024
Revised July 11, 2024
Accepted October 30, 2024

In this paper improved three-parameter model for calculating the IV-curves of photovoltaic converters is proposed. The model is based on dividing the solar cell into current tubes, each of which contains a $p-n$-junction and three resistances — vertical, lateral and an additionally introduced. To determine the model parameters, dark IV-curves and electroluminescence (EL) maps obtained by passing current through the edge of the upper contact grid of a solar cell are used. Using the model, the experimental characteristics of two $Ga_{0.79}In_{0.21}As$ photovoltaic converters with different current collection bus geometries were analyzed and it was shown that the model allows one to describe experimental IV-curves and determine parameters characterizing the quality of the contact grid.

Keywords: Photovoltaic converters, solar cells, spreading resistance, contact resistance.

DOI: 10.61011/SC.2024.10.59948.6619A

Process of current spreading in photovoltaic converters (PVC) plays important role in modes of conversion of high power density of incident radiation typical for lase PVC and solar cells (SC) with concentrators. To model this process different approaches are used, comprising one-dimensional, two-dimensional and three-dimensional models [1–5]. In this paper the tube model is improved [4], it is used to describe current distribution in PVC. The experimental data obtained during study [5] showed the need in introduction in the model of the contact resistance R_C (additionally to vertical R_V and lateral R_L resistances). At that it was identified that R_C and R_L have same effect on current-voltage curves (IV-curves). Contribution of two resistance can be divided when analyzing intensity distribution of electroluminescence (EL) between contacts. For this EL distribution (EL map) over PVC surface was measured when passing current through the structure. EL map analysis identified its more complex view than the three-parameter model predicts not considering brightness decay due to contacts resistance. In this paper EL map of PVC surface was analyzed more detailed which ensures partial consideration of effect of different defects of contact grid. In general use of EL map analysis of PVC surface to study processes of current spreading is widely distributed in literature [6–9]. Thus, in the paper [6] it is shown that the analysis of EL distribution over the surface allows to identify defective contact areas and optimize the technology of their creation. In paper [7] the model is developed to calculate EL distribution over the surface based on equivalent scheme considering resistive components and parameters of $p-n$-junctions. Such approach is suggested in paper [8]. At that in both papers the parameters of $p-n$-junction were set theoretically. The paper [9] presents complex method of experimental distribution of some parameters of SC using IV-curves and EL map. At that unlike to papers [7,8] the authors use simplified equivalent scheme of SC, not considering non-linear nature of current spreading between the contacts, which is important for study presented in this paper.

So, the existing methods either use the simplified models not considering the non-linear effects, or are based on complex equivalent schemes, some their parameters are set theoretically. In this paper we attempted to find a compromise between these two approaches. The used model is based on the previously developed two-parameter tube model [4]. In model the PVC divided into current tubes. Each tube comprises $p-n$-junction and two resistances — vertical R_V and lateral R_L, which considers heterogeneity of current distribution in PVC. The vertical resistance R_V is same for all tubes and generally is determined by properties of the substrate material. The lateral resistance depends on tube number and parameter R_L, which reflects degree of heterogeneity of current distribution. Total resistance for each current rube is expressed by the formula $R = R_V n + R_L x$, where n — number of tubes, and x — tube number.

IV-curve of PVC was calculated as follows. Initially number of current tubes was selected N, then parameters of $p-n$-junction were set (saturation currents $J_{0,j}$ and appropriate diode coefficients A_j, where j — number of considered saturation currents, generally, two — diffusion with $A = 1$ and recombination with $A = 2$). Then parameters R_V and R_L were set. Further IV-curve of tubes was calculated by formula

$$J = \sum_J \left(J_{0,tr,j} \exp\left(\frac{q[V - JR]}{A_j kT} \right) \right), \tag{1}$$

where J — current density, V — applied voltage, k — Boltzmann constant, T — temperature, q — electron charge, $J_{0,tr,j} = J_{0,j}/N$ — saturation currents for current tubes. Summation of the obtained IV-curves of individual „current tubes" ensures total IV-curve of PVC. In this paper

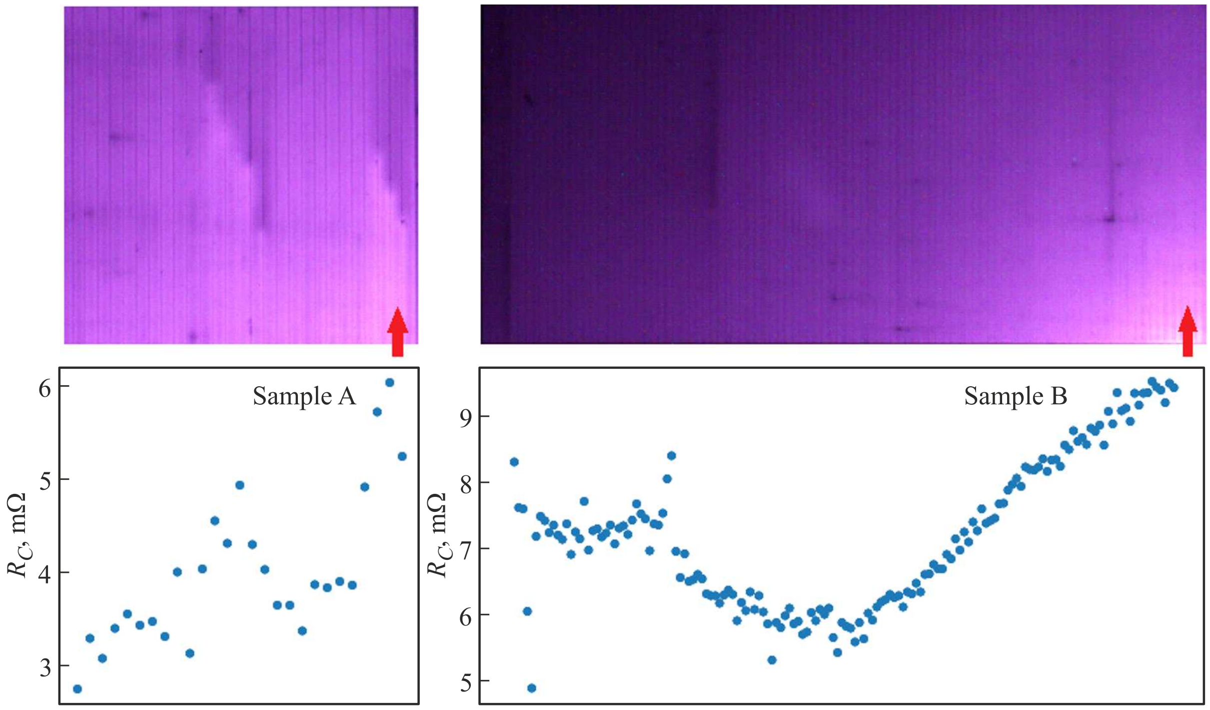

Figure 1. Top: EL map for studied samples upon application of voltage ≈ 0.8 B at current density 1.91 A/cm^2 for sample A and current density 0.75 A/cm^2 for sample B. Bottom: result of resistance calculation for pairs of contact buses — position 0 along X axis corresponds to most left pair of buses on top Figure. Data for sample A are at left, for sample B at right. Orange arrow indicates position of contact application to template when measuring IV-curves and EL maps.

the model is extended — consideration of contact resistance is added. This is performed by contact division into M parts and using the tube model for each part with additional resistance, which proportionally increases with this part removal from busbar (BB). The calculation procedure remains same, but values R and $J_{0,tr,j}$ are calculated as follows: $R = R_V n + R_L x + R_C l$ and $J_{0,tr,j} = J_{0,j}/(NM)$, where l (of 1 to M) — number of contact part. Note that calculation ensures both total IV-curve of device, and determines values of voltages on p–n-junctions for all current tubes, which provides EL intensity distribution, L, over PVC surface. Calculation of EL intensity is based on an exponential dependence L on voltage on p–n-junction:

$$L = L_0 \exp\left(\frac{qV}{kT}\right), \qquad (2)$$

where L_0 — the proportionality coefficient.

The suggested model was applied to analyze two $Ga_{0.79}In_{0.21}As$ PVCs developed under framework on obtaining high-effective PVC of laser radiation [10]. Samples had dimensions $S_A = 0.0784\,\text{cm}^2$, $S_B = 0.9293\,\text{cm}^2$. The first sample is designated in paper as „sample A“, the second one — as „sample B“. Distance between the contact strips in both cases was $100\,\mu$m. Sample A had thinner contact busses, its EL map indicates defects presence in them (Figure 1). To consider the effect of such defects on PVC characteristics dark IV-curves were measured and calculated upon application of contact to the edge of samples. This ensures conditions under which the current spreads initially along BB, and then over contact strips. Such current spreading, this will be shown further, ensures use of the experimental EL map to determine resistance parameters of both strips, and BB.

The obtained dark IV-curves for two samples are given in Figure 2, typical EL map is given in Figure 1. Note that design of the contact grid of sample B contained BB in middle and divided sample into two same parts. Figure 1 shows cross-section of top part. Another part illuminated in similar way. The obtained EL maps decay nonuniformly at distance from the applied contact, which indicates the difference of contact resistance of all strips. In the proposed calculation, using the three-parameter model, this experimental fact was taken into account using the following procedure. Each sample had K pairs of contact strips, each pair, as per three-parameter model, was divided into M parts. So, sample was divided into MK cells. Along BB the cells are enumerated from 1 to K, and along contact strips from 1 to M. Let's designate each cell by two numbers: $x = 1 \ldots K$ — characterizes location along BB and $y = 1 \ldots M$ — characterizes part position along the contact strips. Further from EL map the integral glow of all cells was determined. At place of contact application the glow was considered as maximum (EL intensity $L_{\max}$). It was supposed that in resistance-free section of IV-curve the voltage applied to the entire structure

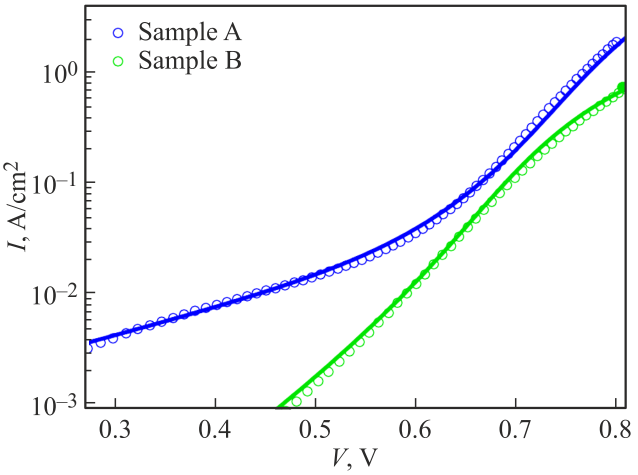

Figure 2. Dark current-voltage curves of studied PVC samples. Dots — experimental data, solid lines — calculation results according to suggested model. Blue color — sample A, green — sample B. (A color version of the figure is provided in the online version of the paper).

Parameters of studied samples*

	Sample A	Sample B
J_{01}, A/cm^2	$1.24 \cdot 10^{-13}$	$0.52 \cdot 10^{-13}$
J_{02}, A/cm^2	$1.07 \cdot 10^{-7}$	$0.45 \cdot 10^{-7}$
J_{0t}, A/cm^2	$7.88 \cdot 10^{-4}$	$7.88 \cdot 10^{-4}$
A_t	6.89	3.60
R_L, $\Omega \cdot$ cm^2	6	6.5
R_V, $\Omega \cdot$ cm^2	0	0
R_{bb}, Ω	3.99	7.22

Note. * J_{01} and J_{02} — diffusion (ideal factor $A = 1$) and recombination ($A = 2$) saturation currents, J_{0t} — tunnel saturation current, A_t — diode coefficient of tunnel current, R_L — lateral resistance of spreading layer, R_{bb} — BB resistance. Besides resistances of all pairs of contact strips are identified, see bottom of Figure 1.

completely drops on this cell (most bright and closest to the applied contact). Then comparison of intensities of electroluminescence of this cell and all other cells ensures determination of voltage dropped on p–n-junctions of rest cells. Considering view (2), for resistance-free section of IV-curve voltage of any cell is set by the expression

$$V(x, y) = V - \frac{kT}{q} \log\left(\frac{L(x, y)}{L_{\max}}\right). \quad (3)$$

Using the obtained voltages, the current in the cells was determined using the measured IV-curves. As a result the maps $V(x, y)$ and $J(x, y)$ were obtained, describing distribution of voltage and current, respectively. At distance from the applied contact $V(x, y)$ drop was observed, which is associated with resistance of contacts. In current model we suppose that this resistance is constant, so the drop was approximated by the linear function. Example of approximation for both samples is shown in Figure 3. Such analysis execution ensured the resistance determination of all pairs of contact strips and BB. At that resistance for pair of strips was determined based on voltage drop along the strip ($x = $ const, y — changes), and BB resistance — based on voltage drop along BB ($y = 1$, x — changes).

To consider losses on BB during calculation of the cell resistance as per procedure presented above the following resistance was used: $R(x, y) = R_V n + R_L x + R_C y + R_{bb} x$, where R_{bb} — BB resistance. Parameters of p–n-junctions were determined by the approximation of the resistance-free section of IV-curve. The parameter R_L was determined based on agreement of calculated IV-curves and experimental curves. During calculation we supposed that effect of the vertical resistance R_V on IV-curve is much lower than of R_L, so R_V was supposed equal to zero. The obtained parameters for two samples are provided in Table, values R_C for all pairs are given below Figure 1, IV-curve calculation result in given in Figure 2. In calculations $N = 50$.

So, the presented study suggest the method for determination of all resistance parameters of PVC affecting the current distribution. The method is based on analysis of dark IV-curves and EL maps obtained when passing current through the contact connected to edge of the top contact grid. Note that measured EL map has more complex view that is predicted by the current model implementation. Thus, experimentally, a monotonic decrease in voltage with

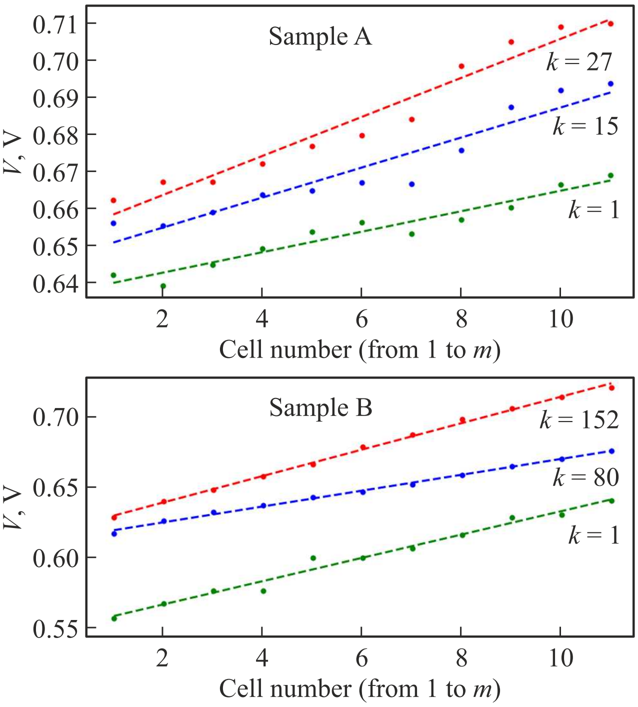

Figure 3. Dependences of voltage along contact strips determined from EL map of studied samples (top — for sample A, bottom — for sample B). Symbols — experimental dots, lines — linear approximation used in paper. Dependences are marked with serial number of pair, k — enumerated from left edge at orientation corresponding to EL map in Figure 1.

distance from the applied contact is not observed, which indicates the need to improve the model. Significant benefits of the model can include its simplicity and possibility to determine based on the experimental data the parameters characterizing quality of top contact grid of PVC and SC, which has high practical value.

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] M. Steiner, S.P. Philipps, M. Hermle, A.W. Bett, F. Dimroth. Progr. Photovolt.: Res. Appl., **1**, 73 (2011).

[2] I. Garcia, C. Algora, I. Rey-Stolle, B. Galiana. Proc. 33rd PVSC (San Diego, USA, May 11–16, 2008) p. 4922908.

[3] B. Galiana, C. Algora, I. Rey. Progr. Photovolt.: Res. Appl., **16**, 331 (2008).

[4] M.A. Mintairov, V.V. Evstropov, S.A. Mintairov, N.Kh. Timoshina, M.Z. Shvarts, N.A. Kalyuzhny. FTP, **50** (7), 987 (2016). (in Russian)

[5] A.D. Malevskays. *Uglerodnye i van-der-vaal'sovy nanostruktury.* Tez. dokl. Molodezhnoj konf. po fizike poluprovodnikov „Zimnya shkola 2024“ (Sankt-Peterburg, Zelenogorsk), 29.02–04.03, 2024) s. 82. (in Russian)

[6] K. Drabczyk, G. Kulesza-Matlak, A. Drygała, M. Szindler, M. Lipiński. Sol. Energy, **126**, 14 (2016).

[7] Z. Hameiri, A. Mahboubi Soufiani, M.K. Juhl, L. Jiang, F. Huang, Y.-B. Cheng, T. Trupke. Progr. Photovolt.: Res. Appl., **23** (12), 1697 (2015).

[8] H. Nesswetter, P. Lugli, A.W. Bett, C.G. Zimmermann. IEEE 38th Photovoltaic Specialists Conf. (PVSC) (2012) pt 2, p. 406.

[9] A. Delamarre. J. Photon. Energy, **2** (1), 027004 (2012).

[10] N.A. Kalyuzhnyy, A.V. Malevskaya, S.A. Mintairov, M.A. Mintairov, M.V. Nakhimovich, R.A. Salii, M.Z. Shvarts, V.M. Andreev. Sol. Energy Mater. Sol. Cells, **262**, 112551 (2023).

Translated by I.Mazurov