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On the collection of photocurrent in solar cells with a contact grid

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Abstract. The exact solution for the dependence of specific power of photoconversion in the mode of maximum collected power on distance l between lines of the contact grid has been obtained. It is shown that in an optimized case, when the change of the potential of heavily doped front layer under contacts and between contacts is less than kT/q, the characteristic length L can be introduced with a meaning of the distance at which the photocurrent reduces by a factor of e due to recombination. Variation of the filling factor of SC IVC due to the presence of contact grid is then analytically expressed via this length.

It is found that in unoptimized case, when the distance between contact strips l is much longer than L, the photocurrent collection is determined by lesser, as compared to L, distance, at which the front layer potential changes from the value of V_m under contacts to the open- circuit voltage between the contacts. In this case the change of IVC filling factor due to the presence of contact grid is expressed again analytically via this new characteristic length.

In the intermediate case, when $l \approx L$, the solution of the problem can be found by numerical methods only.

Keywords: photocurrent collection, contact grid, specific power of photoconversion

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1. Introduction

While considering the question about Ohmic power losses in solar cells (SC) with contact grid the idea is commonly used of sheet resistance of the thin front layer in which the collected current flows and which often provides a main contribution into the series resistance of SC R_s [1-4]. In papers [5-7] the notion of photocurrent collection length L in the front layer was introduced, with a physical meaning of a distance at which the photocurrent reduces by a factor of e due to recombination. The length L allows to estimate rather easily the power losses in SC with contact grid composed of the set of parallel metallic strips.

It should be noted that the very notion of series resistance of SC R_s is valid, in a strict sense, only for an optimized structure, where the variation of potential along the front layer between contacts is small as compared to kT/q (or, which is the same, the distance between contacts l is less than L). In the case when the mentioned modulation is comparable to kT/q, (and $l \geq 2L$), the use of the notions of series resistance in calculations of Ohmic power losses in SC becomes, generally, impossible, and the magnitude and the physical sense of the effective photocurrent collection length change.

In this paper the filling factor of SC I-V characteristics is calculated for a general case when the relation between l and L is arbitrary. It is shown that the use of the notion of the effective photocurrent collection length allows to simplify essentially the calculation of the filling factor of IVC and to generalize it for the case of an arbitrary number of recombination channels.

2. Formulation of the problem

Let us calculate the specific power of photoconversion for the symmetrical structure shown in Figure 1. We assume that the photocurrent flowing in the front n^+ – layer in the z direction can be described in frames of the one-exponential model of IVC:

$$J(z) = J_{sc} - J_0 \cdot (\exp(u(z)/A) - 1), \qquad (1)$$

where $J(z)$ is the photocurrent density, J_{sc} is the density of short-circuit current, J_0 is the density of dark current, $u(z) = qV(z)/kT$ is the dimensionless potential of front n^+ – region, A is the ideality factor of IVC. In the same way as in [6], we consider the linear case in assumption that $\Delta N \ll N_0$, where ΔN and N_0 are integrated over the

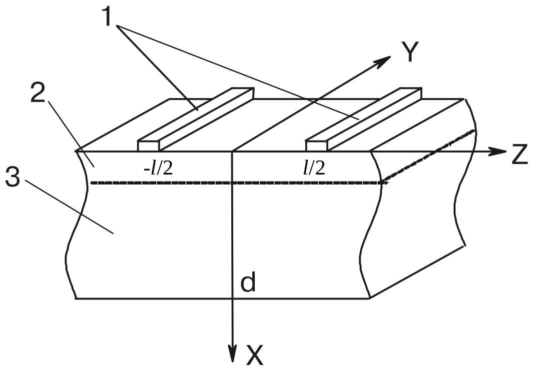

Fig.1. The layout of the structure of the solar cell with contact grid: 1 – metal contacts, 2 – n^+- region, 3 – quasi-neutral bulk of *p*-type.

thickness SC concentrations of extra and equilibrium electrons. Then the continuity equation for the photocurrent flowing in the region $-l/2 < z < l/2$ according to [6] has the following form

$$kT\mu_n N_0 \cdot \frac{d^2u(z)}{dz^2} - J(z) = 0, \quad (2)$$

where μ_n is the mobility of electrons in n^+- layer.

In virtue of the symmetry of the structure, it is sufficient to solve Eq. (2) in the range $0 < z < l/2$, with the following boundary conditions:

$$J(l/2) = J_m = J_{sc} - J_0\left(\exp\left(\frac{u_m}{A}\right) - 1\right), \quad (3)$$

$$\left(\frac{du(z)}{dz}\right)_{z=0} = 0, \quad (4)$$

where $u_m = u_{oc} - A\cdot\ln\left(\frac{u_{oc}}{A}\right)$ is dimensionless voltage of SC in the mode of maximum power collected, $u_{oc} = A\cdot\ln\left(\frac{J_{sc}}{J_0}\right)$ is the dimensionless voltage of open circuit.

The magnitude of photoconversion power for SC of unit area is determined as

$$W = \frac{2}{l}\int_0^{l/2} W(z)dz = \frac{2}{l}\cdot\frac{kT}{q}\int_0^{l/2} J(z)u(z)dz, \quad (5)$$

and the filling factor of IVC, *K*, is equal to:

$$K = \frac{W}{J_{sc}\cdot V_{oc}}, \quad (6)$$

where $V_{oc} = \frac{kT}{q}u_{oc}$ is the open-circuit voltage.

The continuity equation for the electron current flowing in the n^+- region is the analog of the Poisson equation and can be solved in the similar way. Making transition from the integration on coordinate *z* to integration on *u*(*z*) we get the first integral, and the second integral is taken in quadratures. Then, using the boundary conditions (3) and (4) we get the equation connecting *u* and *z*:

$$\int_{u(0)}^{u(z)} \frac{du}{\left((u(0)-u(z)) + \frac{A\cdot J_0}{J_{sc}}\left(\exp\left(\frac{u(z)}{A}\right) - \exp\left(\frac{u(0)}{A}\right)\right)\right)^{1/2}} = -\frac{z}{L_1}, \quad (7)$$

where $L_1 = \left(\frac{kT\mu_n\cdot N_0}{2J_{sc}}\right)^{1/2}$ is the characteristic length.

The constant of integration *u*(0) is found from the equation

$$\int_{u(0)}^{u_m} \frac{du}{\left((u(0)-u(z)) + \frac{A\cdot J_0}{Jsc}\left(\exp\left(\frac{u(z)}{A}\right) - \exp\left(\frac{u(0)}{A}\right)\right)\right)^{1/2}} = -\frac{l}{2\cdot L_1}. \quad (8)$$

The equation set (5)-(8) completely determines the IVC filling factor *K*, however, in a general case, it can be solved only numerically. Let us denote

$$K = K_1\cdot K_2, \quad (9)$$

where $K_1 = \frac{J_m\cdot V_m}{J_{sc}\cdot V_{oc}}$,

$$K_2 = \frac{W}{J_m\cdot V_m}, \quad (10)$$

and *W* is determined by the formula (5). The magnitude K_2 determined in this way reflects only the influence of the contact grid on the IVC filling factor.

In the case when the separation between the strips of the contact grid is sufficiently small, so that modulation of *V*(*z*) is less than *kT/q*, equation (2) is reduced to the diffusion equation with the length

$$L_2 = \left(\frac{q\mu_n\cdot N_0\cdot V_{oc}}{A\cdot J_{sc}}\right)^{1/2}, \quad (11)$$

and K_2 is determined in this case as

$$K_2 = \frac{2L_2}{l}\cdot\tanh\left(\frac{l}{2L_2}\right). \quad (12)$$

As the analysis shows, for the considered case the generalization of the expression for L_2 can be performed without using the IVC of the form (1). At an arbitrary relation between contributions of different recombination channels into the total recombination current the following equation is valid:

$$L_2 = \left(\frac{\mu_n \cdot N_0 \cdot kT}{J_{sc} - J_m} \right)^{1/2}. \qquad (13)$$

The difference $J_{sc} - J_m$ is the density of the total recombination current in the mode of maximum power collected. The relation (13) is valid, in particular, at the nonlinear level of excitation in the quasi-neutral region of SC.

3. Discussion of the results

In Fig. 2 shown are the dependencies of K_2 on the distance between strips of the contact grid *l*. The next parameters were used for calculations: $p_0 = 10^{16}$ cm^{-3}, J_{SC} = 0.04 A/cm^2, J_0 = 3.2 10^{-12} A/cm^2, A = 1, $N_0 = 10^{15}$ cm^{-2}, $\mu_n = 10^2$ cm^2/V s. The curve 1 is the exact one, it is obtained by the numerical integration of Eqs (5), (7), (8). The curve 2 is plotted according to Eqs (11), (12) for the value of L_2 equal, at the mentioned parameters, to 0.491 cm. As can be seen from the figure, at $l / L_2 \le 1$ the curve 2 agrees well with the exact dependence. The curve 3 is obtained from the approximate solution of equation (7) consisting in neglecting the second addend in its denominator. As a result, the quadratic dependence of $V(z)$ on coordinate z is obtained, which is commonly used in calculations of the photoconversion power losses in frames of an approach with the series resistance [4]. As can be seen, the dependence described by the curve (3) gives incorrect result at $l / L_2 \ge 1$ (including the possible change of sign). The curve (4) is plotted according to the equation of the form (12) with the effective photocurrent collection length L_3 equal to 0.241 cm and obtained from the asymptotic of the $K_2(l)$ exact dependence at $l >> L_2$. Within an accuracy of about 5% L_3 coincides with the value $L_4 = 2L_1\sqrt{A \cdot \ln(u_{oc} / A)}$ = 0.255 cm. The magnitude L_4 is equal to the distance, at which potential $V(z)$ in the unoptimized structure, obtained in the above approximation, varies from the value of V_m at the contact to the value of V_{oc} between the contacts. In this case the current is collected only within distances from the contacts that are less than L_4, whereas at longer distances the open circuit mode is realized, and the flowing current is equal to zero. It should be noted that in spite of strong nonlinearity of the expression for $W(z)$ in the considered case, the variation of the filling factor of IVC K_2 related to the presence of the contact grid can be described by the equation of the form (12) beginning from the values $l > 2L_2$.

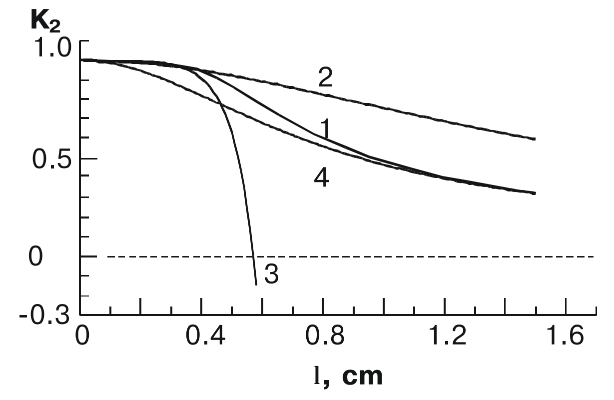

Fig.2. Dependence of variation of the filling factor of IVC related to the presence of the contact grid on the distance between the contacts.

Conclusions

In the present paper the theoretical approach is developed which allow to describe exactly the dependence of the IVC filling factor for SC on the distance between the lines of the contact grid *l* at arbitrary values of *l*. It has been shown that in limiting cases of short and long distances between the contacts in comparison with the photocurrent collection length, the simple equation of the form (12) is valid for the dependence $K_2(l)$ with the length L_2 when $l / L_2 \le 1$, and the length L_3 at $l / L_2 \ge 2$.

References

1. R.J. Handy. Theoretical analysis of the series resistance of solar cells// *Solid -St. Electron* .**10**(8), pp.765-775 (1967)
2. N.C. Wyeth. Sheet resistance component of series resistance in a solar cell as a function of grid geometry// Solid -St. Electron .**20**(7), pp.629-634 (1977)
3. A.M.Vasil'ev, A.P.Landsman. *Poluprovodnikovye fotopreobrazovateli* (Semiconductors Photoconvertors). Moscow: Sovetskoe Radio, 1971 (in Russian).
4. A.L.Fahrenbruch, R.H.Bube. Fundamentals of solar cells. Photovoltaic solar energy conversion, New York, 1983
5. A.V.Sachenko, A.I.Shkrebtii. Mechanizmy sobiraniya fototoka v solnechnykh elementakh s kontaktnoi setkoi (Mechanisms of photocurrent collection in solar cells with contact grid) // *Ukr. Fiz. J.*, **29** (12), pp.1855-1859 (1984) (in Russian).
6. A.V. Sachenko, A.I.Shkrebtii, T.V.Panichevskaya. Teoreticheskaya model solnechnogo elementa s kontaktnoy setkoy (Theoretical model of solar cell with contact grid) // *Optoelectronika i Poluprovodnikovaya Tekhnika*, No.21, pp.63-70 (1991) (in Russian).
7. A.P.Gorban', A.V. Sachenko,S.I.Frolov. Analiz effektivnosti kremnievykh fotopreobrazovatelei s indutsirovannymi bar'erami v usloviyakh var'iruemogo spectral'nogo sostava solnechnogo izlucheniya (The analysis of efficiency of silicon photoconvertors with induced barriers in conditions of variable spectral composition of solar radiation) // *Optoelectronika i Poluprovodnikovaya Tekhnika*, No.16, pp.80-84 (1989) (in Russian).