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Efficiency limit for diffusion silicon solar cells at concentrated illumination

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Abstract. A general approach has been developed to calculation of photoconversion efficiency of thin-base silicon solar cells with double-sided metallization for concentrated solar illumination. The full absorption of photoactive radiation has been theoretically simulated, the light absorption by free charge carriers in heavily doped regions in AM0 conditions was taken into account. It was found that the efficiency of photoconversion η at $K \approx 100$ can be as high as 27%.

Keyword: photoconversion efficiency, silicon solar cells, concentrated illumination

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1. Introduction

In papers [1-4] a construction of silicon solar cells (SC) was suggested with point contacts located at the back surface to be used in conditions of concentrated solar illumination. In this case, due to application of high-purity silicon with long carrier lifetime, the authors managed to enhance the photoconversion efficiency in AM0 conditions 1.5 up to 28% at the concentration factor of solar illumination $K \approx 100$. On the other hand, in the mentioned structure, as K increases, the short-circuit current, normalized by this value, should slightly decrease. This occurs due to an increasing role of Auger recombination which results in a reduction of the diffusion length of non-equilibrium charge carriers in the base region.

In this paper presented is the theoretical analysis of the efficiency of silicon diffusion SC with the standard configuration using a thin base in AM0 conditions. It is shown that a reduction of the short-circuit current at concentrated illumination may be absent, and the maximum efficiency at $K \approx 100$ can exceed 27%. The requirements to the layout of a top contact grid are analyzed enabling to minimize the ohmic power losses related to the presence of sheet resistance of front n^+-region. The opportunities of reduction of effective surface recombination rates at front and back surfaces of SC for the case of the high excitation level have been studied theoretically.

2. Formulation of the problem and theoretical analysis

2.1. Mechanisms of photogeneration, bulk and surface recombination

Consider $n^+ - p - p^+ -$ structure (see Fig.1) with equilibrium concentrations of electrons and holes in the base n_0 and p_0, respectively. We will assume that its thickness d is less than the diffusion length of minority carriers in the base L, and the front contact is a system of narrow parallel metal strips united by a conducting bus. The relative (normalized by the SC area A) areas of the bus and of parallel strips are m_1 and m_2, respectively. The contact grid is supposed to be sufficiently dense and, in the short-circuit mode, collects the current without losses. The last assumption allows us to restrict ourselves by the solution of the one-dimensional problem [5]. The specific calculations are carried out for $A = 1$ cm^2. The function of photogeneration of electron-hole pairs in the semiconductor can be expressed as

$$g\ (\lambda) \cong \frac{\alpha(\lambda) I \sqrt{R_0}\left(e^{-\alpha(\lambda)x} + R_d R_2 e^{\alpha(\lambda)x - 2\alpha(\lambda)d}\right)}{1 - R_0 R_d R_1 R_2 e^{-2\alpha(\lambda)d}}, \quad (1)$$

where $\alpha(\lambda)$ is the light absorption factor, λ is the irradiation wavelength, I is the intensity of light that penetrates into the semiconductor, R_1 and R_2 are reflection coefficients for light incident to the front and back surfaces from the semiconductor bulk (in the case of total absorption of light in semiconductor [6] $R_1 = R_2 = 1$), R_0 and R_d are attenuation coefficients of irradiation intensity that take into account the light absorption by free charge carriers in heavily doped n^+ - and p^+ - regions and are equal, respectively, to

$$R_0 = \exp(-2\alpha_n x_n), \quad R_d = \exp(-2\alpha_p x_p), \tag{2}$$

where α_n and α_p are factors of absorption by free electrons and holes in silicon [7], which are equal, in absence of compensation, at T = 300 K

$$\alpha_n = 1.8 \cdot 10^{-39} N^2 (\lambda/\mu\mathrm{m})^{3.5},$$

$$\alpha_p = 1.0 \cdot 10^{-39} P^2 (\lambda/\mu\mathrm{m})^{3.5}. \tag{3}$$

Here x_n and x_p are thicknesses of $n^+ -$ and p^+ - regions, N and P are electron and hole concentrations in these regions for the case of step-like concentration dependencies on coordinate x (Fig.1a).

In calculations the following mechanisms of recombination in the base have been taken into account: Shokley-Reed recombination, radiative band-to-band recombination and Auger band-to-band recombination. In the used approximation, $d << L$, the excess concentration of electrons in the base $\Delta n(x) \cong \mathrm{const}$. Then, for the flow of bulk recombination R_v, the following equation is valid:

$$\begin{aligned} R_v = \Delta n \cdot d \cdot \Big[& \tau_r^{-1} + A_i(p_0 + \Delta n) + \\ & + B_p(p_0 + \Delta n)^2 + B_n(p_0 + \Delta n)\Delta n \Big], \end{aligned} \tag{4}$$

where τ_r is the Shokley-Reed recombination lifetime, A_i, B_p, B_n are constants of band-to-band radiative Auger recombination for electrons and holes, the numerical values of which are adduced below [8, 9]:

$$A_i \approx 1.48 \cdot 10^{-15} \mathrm{cm^3 s^{-1}}, \quad B_p \approx 10^{-31} \mathrm{cm^6 s^{-1}},$$

$$B_n \approx 2.8 \cdot B_p.$$

When obtaining the expressions for effective rates of surface recombination at front and back surfaces S_0 and S_d, it was taken into account that recombination takes place in a different way under the contacts and in the spaces between contacts. The Auger recombination in the bulk of $n^+ -$ and p^+ - regions, the charge carrier degeneration in them and narrowing of the bandgap due to heavy doping were also taken into account. As a result, in the framework of the diode theory the following expressions were obtained for S_0 and S_d:

$$S_0 = r_0 \cdot \left(1 + \frac{\Delta n}{p_0}\right), \tag{5}$$

$$r_0 = \frac{p_0}{N_c} V_p e^{-Z_n + \Delta E_n} \left[m_0 \frac{S_{m0} \cosh \frac{x_n}{L_p} + V_p \sinh \frac{x_n}{L_p}}{S_{m0} \sinh \frac{x_n}{L_p} + V_p \cosh \frac{x_n}{L_p}} + \right.$$

$$\left. + (1 - m_0) \frac{S_{r0} \cosh \frac{x_n}{L_p} + V_p \sinh \frac{x_n}{L_p}}{S_{r0} \sinh \frac{x_n}{L_p} + V_p \cosh \frac{x_n}{L_p}} \right], \tag{6}$$

$$S_d = r_d \cdot \left(1 + \frac{\Delta n}{p_0}\right), \tag{7}$$

$$r_d = \frac{p_0}{N_v} V_n e^{-Z_p + \Delta E_p} \left[m_d \frac{S_{md} \cosh \frac{x_p}{L_n} + V_n \sinh \frac{x_p}{L_n}}{S_{md} \sinh \frac{x_p}{L_n} + V_n \cosh \frac{x_p}{L_n}} + \right.$$

$$\left. + (1 - m_d) \frac{S_{rd} \cosh \frac{x_p}{L_n} + V_n \sinh \frac{x_p}{L_n}}{S_{rd} \sinh \frac{x_p}{L_n} + V_n \cosh \frac{x_p}{L_n}} \right]. \tag{8}$$

Here, N_c and N_v are effective densities of states in the conduction band and in the valence band, $V_{p(n)}$, $D_{p(n)}$, $L_{p(n)}$, are, respectively, velocity, coefficient and length of diffusion of holes (electrons) in $n^+(p^+)$ - regions, correspondingly, $V_{p(n)} = D_{p(n)}/L_{p(n)}$, $S_{m0(d)}$, $S_{r0(d)}$ are «true» recombination rates of holes (electrons) at the boundary of the strongly doped $n^+(p^+)$-region with metal and dielectric, respectively, $\Delta E_{n(p)}$ is the narrowing of bandgap in $n^+(p^+)$-layer due to the effect of heavy doping (in kT units), $m_0 = m_1 + m_2$ and m_d are degrees of metallization of front and back surfaces, and $Z_{n(p)}$ is determined from the equation $F_{1/2}(Z_{n(p)}) = N/N_{c(v)}$, where $F_{1/2}(Z_{n(p)})$ is the Fermi-Dirac integral of the order of 1/2.

The first terms in brackets of (6), (8) are related to the total recombination under contacts, and the second ones describe the recombination in the intercontact spaces.

2.2 Efficiency of photoconversion

The density of the short-circuit current of SC J_{SC} in AM0 conditions at 300 K for the case when the solar emission spectrum is approximated by that of absolutely black body at T_C = 5800 K is determined by the expression:

$$J_{SC} = 0.45046 \cdot (1 - m_0) \cdot K \int_0^1 \frac{\left[f_p(z) + f_n(z) \right]}{z^4 (\exp(2.207/z) - 1)} \cdot dz, \tag{9}$$

where $z = \lambda/\lambda_x$, λ_x is the red edge of the intrinsic photoeffect in silicon,

$$f_p(z) = \frac{\alpha L_p \sqrt{R_0}}{1 + \alpha L_p} \times$$

$$\times\left[\frac{S_{r0}\left(1-\mathrm{e}^{-\alpha x_n+\frac{x_n}{L_n}}\right)+V_p\left(\alpha L_p-\mathrm{e}^{-\alpha x_n+\frac{x_n}{L_n}}\right)}{(\alpha L_p)\cdot\left[S_{r0}\sinh\left(\frac{x_n}{L_p}\right)+V_p\cosh\left(\frac{x_n}{L_p}\right)\right]}-\mathrm{e}^{-\alpha x_n}\right], \quad (10)$$

$$f_n(z)=-\frac{\alpha L\cdot\sqrt{R_0}}{(\alpha^2L^2-1)\cdot\left[1-R_0R_1R_2R_d\mathrm{e}^{-2\alpha d}\right]}\times$$
$$\times\left\{\left[(r_d+V)\cdot\mathrm{e}^{\frac{d-x_n}{L}}+(r_d-V)\cdot\mathrm{e}^{\frac{-d+x_n}{L}}\right]\times\right.$$
$$\times\left[\mathrm{e}^{-\alpha x_n}+R_2R_d\mathrm{e}^{-2\alpha d+\alpha x_n}\right]+$$
$$\left.+2\left[\alpha D(1-R_2R_d)-r_d(1+R_2R_d)\right]\mathrm{e}^{-\alpha d}\right\}\times$$
$$\times\left[(r_d+V)\cdot\mathrm{e}^{\frac{d-\alpha x_n}{L}}-(r_d-V)\cdot\mathrm{e}^{-\frac{d-\alpha x_n}{L}}\right]^{-1}+$$
$$+\frac{\sqrt{R_0}\cdot(\alpha L)^2\left[\mathrm{e}^{-\alpha x_n}-R_2R_d\mathrm{e}^{-2\alpha d+\alpha x_n}\right]}{(\alpha^2L^2-1)\cdot\left[1-R_0R_1R_2R_d\mathrm{e}^{-2\alpha d}\right]}, \quad (11)$$

where $f_p(z)+f_n(z)-$ is the photocurrent collection factor, $\alpha\equiv\alpha(z)$, $V=\frac{D}{L}$, *D* and *L* are diffusion coefficient and length of electrons in the base.

For deriving equations (10) and (11) the standard procedure was applied consisting in a solution of diffusion equations for excess of holes and electrons in n^+-region and the base using boundary conditions for the flow of holes and electrons in planes *x* = 0 and *x* = *d*, respectively.

EMF of open circuit V_{OC}, being the sum of voltage drops near front and back contacts, during illumination equals to [9]:

$$V_{OC}=\frac{kT}{e}\cdot\ln\left[\frac{\Delta n}{n_0}\cdot\left(1+\frac{\Delta n}{p_0}\right)\right]. \quad (12)$$

The excess electron concentration Δn in the open circuit mode is found from the equation of balance of generation and recombination flows, which has the form:

$$J_{SC}/e=R_v(\Delta n)+(S_0+S_d)\cdot\Delta n\,. \quad (13)$$

It follows from (13) that in the open circuit mode the next relation is valid

$$\Delta n=-\frac{p_0}{2}+\left[\frac{p_0^2}{4}+n_i^2\exp\left(\frac{eV_{OC}}{kT}\right)\right]^{1/2}. \quad (14)$$

During the photocurrent flow, when $V=J(V)(R_H+R_s)<V_{OC}$, where R_H is the load resistor, and R_s is the series resistance, instead of (13) we get the following equation for I-V characteristic of SC:

$$J(V)=J_{SC}-eR_v(\Delta n^*)-eS_0(\Delta n^*)\cdot\Delta n^*-eS_d(\Delta n^*)\cdot\Delta n^*, \quad (15)$$

where the magnitude Δn^* is determined from Eq. (14) with V_{OC} substituted by *V*. Using the condition of maximum collected power *P* = *J*(*V*)·*V*, we get the transcendent equation for determination of V_m and then find the photoconversion efficiency η. With account of ohmic power dissipation, in approximation that the idea of series resistance of SC is applicable [11] and the resistance of the contact grid can be neglected, the value of η can be found from the expression

$$\eta=\frac{J(V_m)\cdot V_m}{0.136\cdot K}\cdot\frac{2L_c\cdot m_2}{l_n(1-m_2)}\tanh\left(\frac{l_n(1-m_2)}{2L_c\cdot m_2}\right), \quad (16)$$

where 0.136 W/cm^2 is the specific power of solar irradiation in AM0 conditions, l_n is the width of a strip of the frontal grid, $L_c=\left(\frac{\mu_n\cdot N\cdot x_n\cdot kT}{J_{sc}-J(V_m)}\right)^{1/2}$ is the effective photocurrent collection length, μ_n is the electron mobility in the n^+-region.

3. Results of calculation and discussion

In calculations we assumed that recombination in the bulk of n^+- region takes place according to Auger mechanism and $\tau_p=(B_nN^2)^{-1}$, and the empirical equations [12, 13] were used:

$$L_p(N)=4.02\cdot10^{14}(N)^{-0.951},$$
$$\Delta E_{n(p)}=0.0124\,N(P)/n_i)^{0.25}, \quad (17)$$

where n_i is carrier concentration in intrinsic semiconductor. Similarly, it was assumed that recombination in the bulk of p^+-region is also determined by Auger mechanism with $\tau_n=(B_pP^2)^{-1}$, and the electron diffusion coefficient is equal to 7 cm^2/s [14].

In the present paper the following values of parameters were used for calculation of the short-circuit current and efficiency of photoconversion intrinsic to SC: p_0=10^{14} cm^{-3}, *d* = 10^{-2} cm, $\tau_r=0.025c$, R_1 = R_2 = 1, S_{m0} = S_{md} = 2.5·10^6 cm/s, S_d = 0, S_{r0} = S_{rd} = 10^3 cm/s, m_1 = 0.025, l_n = 15μm, m_2 = 0.025 (except Figure 5). In calculations the dependence $\alpha(\lambda)$ from the paper [15] was used. The choice of the base doping level is justified, on the one hand, by the fact that in this case the highest bulk lifetime τ_r can be provided, and, on the other hand, as it was shown in [10], at $\tau_r\geq10^{-2}$ s the efficiency factor η no longer depends on p_0 in the wide range of base doping levels.

Fig.1b shows the dependencies of the short-circuit

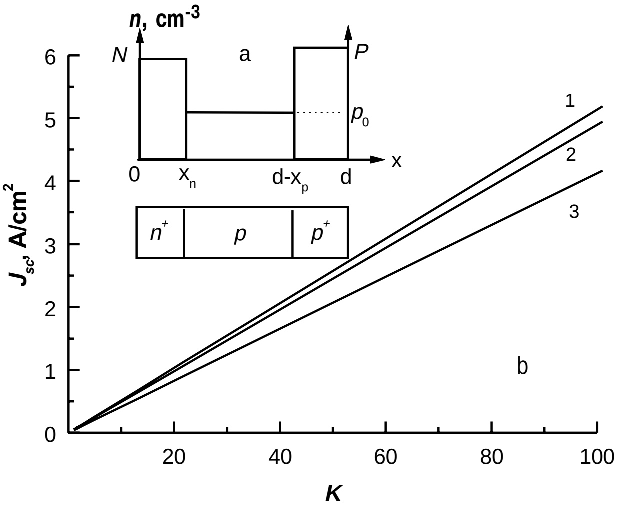

Fig.1. a - the schematic layout of solar cell; b - dependence of the SC short-circuit current on the concentration factor of solar radiation at following parameter values: N=10^{19} cm^{-3}, $x_n = 5\cdot10^{-6}$ cm (1); N=10^{21} cm^{-3}, $x_n = 5\cdot10^{-6}$ cm (2); $N = 10^{21}$ cm^{-3}, $x_n = 3\cdot10^{-5}$ cm (3);

current on concentration factor of solar radiation. It can be seen from the figure, that the magnitude of J_{SC} is linear in dependence on K. Besides, the less are the doping level N of the n^+ – region and its thickness x_n, the higher is the magnitude of the short-circuit current. This is related to the reduction of the short-circuit current due to Auger recombination in the bulk of n^+ – region, and also to losses in this region due to light absorption by free carriers.

It should be noted that due to action of the Bugger-Lambert law and due to limitation of recombination by the diffusion supply, the concentration of excess charge carriers in the base in the short-circuit mode in the structures with back metallization significantly increases, as compared to the case of a standard SC construction. This results in the sub-linear dependence of the short-circuit current on the magnitude of K due to presence of Auger recombination in the base [4].

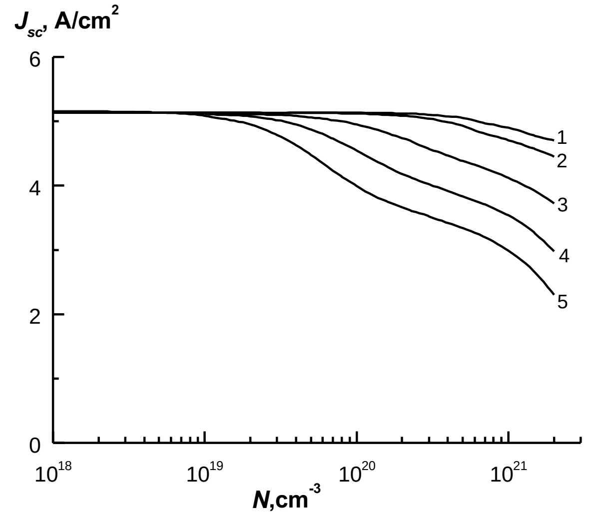

Fig.2. Dependences of the SC short-circuit current on doping level of n^+-region for K = 100 at $x_n = 5\cdot10^{-6}$ cm (1); 10^{-5} cm (2), $3\cdot10^{-5}$ cm (3), $6\cdot10^{-5}$ cm (4), 10^{-4} cm (5).

In Fig.2 shown are the dependencies of short-circuit current on the doping level N of n^+ – region more clearly exhibiting the influence of mentioned losses. It can be seen in the figure that the more is the thickness of n^+ – region, the greater is the reduction of short-circuit current at high values of N.

In Fig.3 the dependencies of photoconversion efficiency on the degree of concentration of solar irradiation are presented. The magnitude of η grows with increasing K due to the rise of photovoltage in the mode of maximum power collection. The more is the effective rate of surface recombination S_0, the less is the value of η.

In Fig.4 presented are the dependencies of photoconversion efficiency on the doping level of

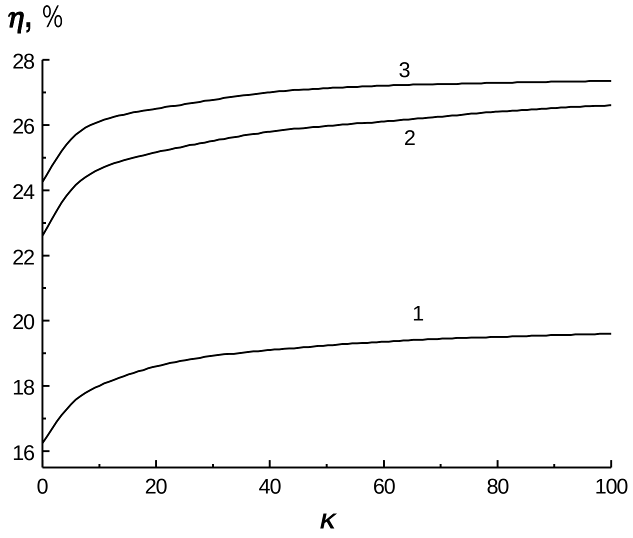

Fig.3. Dependences of SC photoconversion efficiency on concentration factor of solar irradiation at following parameter values: $N = 10^{20}$ cm^{-3}, $x_n = 10^{-4}$ cm (1); $N = 6\cdot10^{20}$ cm^{-3}, $x_n = 10^{-5}$ cm (2); $N = 10^{21}$ cm^{-3}, x_n=$5\cdot10^{-6}$ cm (3);

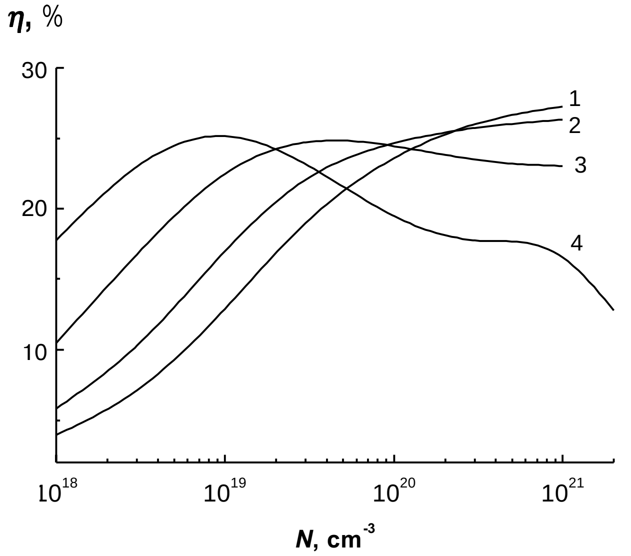

Fig.4. Dependences of SC photoconversion efficiency on doping level of n^+-region for K = 100 at following parameter values: $x_n = 5\cdot10^{-6}$ cm (1); 10^{-5} cm (2), $3\cdot10^{-5}$ cm (3), 10^{-4} cm (4).

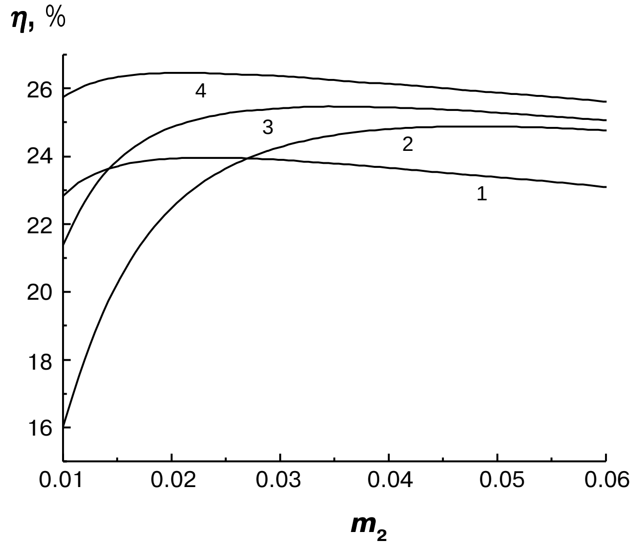

Fig.5. Dependences of SC photoconversion efficiency on specific area of metallization of front surface by the transverse strips m_2 for $\mu_n = 10^2$ cm²/V·s at following parameter values: $N = 10^{19}$ cm^{-3}, $x_n = 10^{-4}$ cm, $K = 10$ (1); $N = 10^{19}$ cm^{-3}, $x_n = 10^{-4}$ cm, $K = 100$ (2); $N = 3\cdot10^{20}$ cm^{-3}, $x_n = 10^{-5}$ cm, $K = 100$ (3); $N = 10^{21}$ cm^{-3}, $x_n = 10^{-5}$ cm, $K = 100$ (4).

n^+ – region. As seen from the figure, in the range of relatively small values of N ($\leq 10^{19}$ cm^{-3}), the value of η rises with increasing the thickness of n^+ – region. It is explained by the reduction of the value of S_0, as x_n increases. At the same time, at high doping levels of n^+ – region ($\geq 10^{20}$ cm^{-3}), the value of η is less, the more is the value of x_n, which is related to the decreasing the short-circuit current owing to recombination in the bulk of n^+ – region and to light absorption by free charge carriers.

It should be noted that, as calculations show, the maximum value of η is reached at high values of N and P, when the effective rates of surface recombination S_0 and S_d are small ($\leq$ 1 cm/s), and at small thicknesses of n^+ – region ($\leq 10^{-5}$ cm), when the losses caused by Auger recombination in the bulk of n^+ – region and light absorption by free charge carriers are negligible. The maximum value of η, as seen from the figure, at $K \approx 100$ is above 27%.

Fig. 5 shows the dependence of SC photoconversion efficiency η on the distance between the lines of contact grid, characterized by the magnitude m_2. At small values of m_2, when the distance between contact strips is large, η reduces due to ohmic power losses at the series resistance of n^+ – region, and at large values of m_2 the decrease of η is related to the reduction of the short circuit current owing to shadowing the SC surface by the contact grid. As seen from curves 1 and 2, with increasing the concentration of the solar irradiation, the maximum of η is shifted toward greater values of m_2.

4. Conclusions

It has been shown theoretically that the photoconversion efficiency limit of diffusion silicon SC with double-sided metallization can reach the value of 27% in conditions AM0 at the degree of irradiation concentration solar close to 100. To get such an efficiency, it is necessary to minimize the effective rates of surface recombination at front and back surfaces, which is provided, in particular, by heavy doping of n^+ – and p^+ – regions and by the decrease of the front p n - junction depth.

It was shown that theoretical dependencies of the short-circuit current of thin-base silicon diffusion SC with double metallization are linear in dependence on the degree of solar irradiation concentration K in the considered range of K variation.

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