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Effect of emitter properties on the conversion efficiency of silicon solar cells

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Abstract. The effect of donor concentration distribution *N(x)* in the n^+-emitter on the conversion efficiency h of silicon n^+-p-p^+ solar cells is studied theoretically. Shockley-Reed-Hall recombination in the emitter is taken into consideration together with band-to-band Auger recombination. The calculation is performed in the approximation when in the region with changing concentration a small part of generated electron-hole pairs recombines.
It is shown that, in general, the correlation between h and *p-n* - junction depth is absent.

Keywords: silicon solar cell, photoconversion effiiciency, *p-n* junction.

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1. Introduction

The conversion efficiency is known to depend essentially on such characteristics of highly doped n^+-emitter of solar cell (SC) as its sheet resistance, doping level, *p-n* - junction depth and also the minority carrier lifetime in the highly doped region [1-3]. In our paper [4], at rather general assumptions, the theoretical relations were derived allowing the efficiency of diffusion silicon SC to be calculated for the spectral conditions AM0 and the optimization of solar cells to be carried out on such parameters as the base doping level p_0, SC thickness d, degree of shadowing of the front surface by the contact grid, and also the doping level and thickness of the n^+-emitter. In that paper the model of step-like dependence of the doping level in the emitter on the coordinate x directed normally to the SC surface was used. Besides, the hole lifetime in the emitter was assumed to be determined by the time of band-to-band Auger recombination.

In this paper, while calculating the conversion efficiency in frames of the analytical approach, the presence of the region in the emitter where the electron concentration decreases with increasing x was taken into account. Besides, Auger recombination and Shockley-Reed-Hall recombination with the lifetime τ_{rp} are taken into account, which allowed to consider theoretically the efficiency of SC with the so called «dead» layer at the front surface [1].

2. Formulation of the problem

The impurity distribution profile in the n^+- p- p^+ -structure analyzed in this paper, is schematically shown in Fig.1. Firstly, we will consider the case when the *p-n*-junction depth x_n equals to the sum of x_{n0} region thickness, where the donor concentration does not depend on the coordinate x, and of Δx_n region thickness, where the donor concentration varies with x. As shown in [1,5], such $N(x)$ profiles in diffusion silicon SCs are rather typical. Besides, exponential dependences of the form $N_0 \cdot \exp\left(\frac{-x}{x_0}\right)$ (curve 1) are often observed either in the whole emitter region or in the essential part of it. The *p-n*-junction depth, x_n, in the above model is determined by the equation

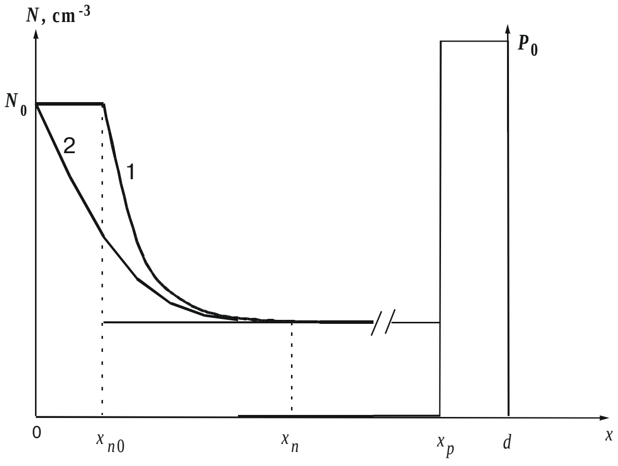

Fig.1. Schematic view of the impurity distribution in the emitter region of silicon solar cell.

$$x_n = x_{n0} + x_0 \ln\left(\frac{N_0}{p_0}\right), \tag{1}$$

where N_0 is the maximum donor concentration in the emitter. The case of classical diffusion impurity profile in the emitter $N(x) = N_0\,\mathrm{erfc}(x/x_1)$ (curve 2) is also analysed.

The hole lifetime in the highly doped n^+ - region we assume to be equal to

$$\tau_p = \left(\frac{1}{\tau_{rp}} + C_n N(x)^2\right)^{-1}, \tag{2}$$

where $C_n = 2.8\cdot10^{-31}$ cm^{6}s^{-1} is the Auger recombination constant for electrons in silicon [6]. We will also assume the excess concentration of minority charge carriers in the base at the interface between the space charge region and the quasi-neutral bulk near the front contact $\Delta n(x_n+w_0)$ to be small as compared to the equilibrium hole concentration in the base. For the electron lifetime in the base, the relation is valid:

$$\frac{1}{\tau_n} = \frac{1}{\tau_{rn}} + A_i\cdot p_0 + C_p\cdot p_0^2, \tag{3}$$

where τ_{rn} is the Shockley-Reed-Hall recombination lifetime, $A_i = 1.48\cdot10^{-15}$ cm^{3}s^{-1} is the photon-emitting recombination constant at $T = 300$ K [4], $C_p = 10^{-31}$ cm^{6}s^{-1} is the Auger recombination constant for holes [6].

The effective recombination rate at the SC top surface, S_0, can be written as follows [7]:

$$S_0 = V_p \frac{p_0}{N_c} e^{\Delta E_g^{(n^+)} - Z_n} \times \tag{4}$$
$$\times\left[\frac{\left(S_{pm}\cosh\left(\frac{x_{n0}}{L_p}\right) + V_p\sinh\left(\frac{x_{n0}}{L_p}\right)\right)m}{S_{pm}\sinh\left(\frac{x_{n0}}{L_p}\right) + V_p\cosh\left(\frac{x_{n0}}{L_p}\right)} + \right.$$
$$\left. + \frac{\left(S_r\cosh\left(\frac{x_{n0}}{L_p}\right) + V_p\sinh\left(\frac{x_{n0}}{L_p}\right)\right)(1-m)}{S_r\sinh\left(\frac{x_{n0}}{L_p}\right) + V_p\cosh\left(\frac{x_{n0}}{L_p}\right)}\right],$$

where $V_p = D_p/L_p$, D_p, L_p are the diffusion velocity, diffusion coefficient and diffusion length for holes in highly doped n^+-region, respectively, N_c is the effective density of states in the conduction band of silicon, Δ is the magnitude of the silicon band-gap reduction in the n^+-emitter (in kT units), and the magnitude Z_n is determined from the equation

$$N_0 = N_c\cdot F_{1/2}(Z_n), \tag{5}$$

where N_0 is the maximum electron concentration in the emitter, $F_{1/2}(Z_n)$ is Fermi-Dirac integral of the order 1/2, S_{pm} and S_r are «true» rates of surface recombination at the semiconductor-metal and semiconductor-dielectric interfaces, respectively, x_n is the thickness of the emitter, m is the ratio of the front contact grid area to the total area of SC surface.

For the effective recombination rate at the back surface, S_d, like that in (4), we have:

$$S_d = V_n \frac{p_0}{N_v}\exp\left(\Delta E_g^{(p^+)} - Z_p\right)\times$$
$$\times\left[\frac{S_{nm}\cosh\left(\frac{x_p}{L_n}\right) + V_n\sinh\left(\frac{x_p}{L_n}\right)}{S_{nm}\sinh\left(\frac{x_p}{L_n}\right) + V_n\cosh\left(\frac{x_p}{L_n}\right)}\right], \tag{6}$$

where $V_n = D_n^+ / L_n$, D_n^+, L_n are diffusion velocity, diffusion coefficient and diffusion length for electrons in the highly doped p^+- region, respectively, N_v is the effective density of states in the valence band of silicon, $\Delta E_g^{(p^+)}$ is the reduction of the silicon band-gap in the p^+- region (in kT units), the magnitude Z_p is determined from the equation

$$P = N_v\cdot F_{1/2}(Z_p), \tag{7}$$

where P is the hole concentration in the p^+- region, S_{nm} is the «true» recombination rate at the semiconductor-metal interface, x_p is the thickness of the p^+- region.

It should be noted that the first term in the brackets of (4) is responsible for the recombination under contacts and the second term — for the recombination in the inter-contact spaces. As well as the surface recombination in (4), the recombination in the bulk of the highly doped emitter was taken into account. In calculations the parameters $S_{pm} \cong S_{nm} \cong 2.5\cdot10^6$ cm/s and, also, the following expression for the electron lifetime in the p^+-region were used:

$$\tau_{n^+} = \left(C_p\cdot P^2\right)^{-1}. \tag{8}$$

Besides, it was suggested that the following empirical dependence for the diffusion length of holes in the emitter on its doping level is valid [8]:

$$L_p = 4.02\cdot10^{14}\cdot N^{-0.951}. \tag{9}$$

In the equation (9) dimension of L_p is cm, and that of N is cm^{-3}. The diffusion coefficient for electrons in the highly doped p^+- region, D_{n^+}, was taken to be equal to 7 cm^2/s [9]. For dependences $\Delta E_g^{(n^+)}(N)$ and $\Delta E_g^{(p^+)}(P)$ the empirical relations from [10] were used:

$$\begin{aligned} \Delta E_g^{n^+}(N) &= 0.0124\cdot\left(\frac{N}{n_i}\right)^{0.25}, \\ \Delta E_g^{p^+}(P) &= 0.0124\cdot\left(\frac{P}{n_i}\right)^{0.25}. \end{aligned} \tag{10}$$

The value of SC short-circuit current density (in A/cm^2 units) in AM0 conditions (when the solar radiation spectrum is substituted by the radiation of absolutely black body at $T_c = 5800$ K) at the ambient temperature 300 K is determined from the equation:

$$J_{sc} = 0.4505 \cdot (1-m) \cdot (1-r_s) \cdot \int_0^1 \frac{f_p(\alpha(z)) + f_n(\alpha(z))}{z^4 \cdot \left[\exp\left(\frac{2.207}{z}\right) - 1\right]} dz, \tag{11}$$

where r_s is the reflection coefficient for the top SC surface, $z = \lambda/\lambda_x$, λ is the wavelength of the incident light, λ_x is the red boundary for intrinsic photon absorption in silicon, $f_p(\alpha)$ and $f_n(\alpha)$ are the spectral dependences of collection coefficients for holes in the emitter and that for electrons in the p-region, $\alpha(z)$ is the spectral dependence of light absorption coefficient, the analytical expression for which is presented in [11].

The function of electron-hole pair generation in semiconductor, according to the model suggested in [12], is described by the expression:

$$g(\alpha, x) \cong \alpha \cdot I \frac{\left(\exp(-\alpha x) + R_d \cdot \exp(-2\alpha d + \alpha x)\right)}{1 - R_0 R_d \cdot \exp(-2\alpha d)}, \tag{12}$$

where I is the monochromatic illumination intensity, R_0 and R_d are reflection coefficients for photons moving to the top and rear surfaces from the sample bulk. The relation $R_0 = R_d = 1$ models the case of total light absorption in the semiconductor bulk that may occur in the case of textured or profiled surfaces of SC.

Two approximations were used for determining $f_p(\alpha)$. The first one consists in the assumption that in the region of the $N(x)$ gradient ($x_{n0} \le x \le x_n$) high electrical field exists, the strength of which, kT/qx_0, exceeds essentially the strength of the diffusion field kT/qL_p, where $L_p = \left(D_p\left(\frac{1}{\tau_{rp}} + C_n N(x)\right)^{-1}\right)^{1/2}$ is the hole diffusion length in the n^+-region. In this approximation the electron-hole recombination in the ($x_{n0} \le x \le x_n$) region can be neglected, and the collection coefficient for non-equilibrium charge carriers generated in this region is equal to 1. The standard procedure for calculating the diffusion flux for holes at the boundary of n^+-region and for electrons in the $x = x_n$ plane in this case gives

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

$$\times \left[\frac{\left(S_r + V_p \cdot \alpha L_p\right) - \exp\left(-\alpha x_{n0} + \frac{x_{n0}}{L_p}\right)\left(S_r + V_p\right)}{\left(\alpha L_p - 1\right) \cdot \left[S_r \operatorname{sh}\left(\frac{x_{n0}}{L_p}\right) + V_p \operatorname{ch}\left(\frac{x_{n0}}{L_p}\right)\right]} - \exp\left(-\alpha x_{n0}\right)\right]$$

$$+ \left[\exp\left(-\alpha x_{n0}\right) - \exp\left(-\alpha x_n\right)\right], \tag{13}$$

where $L = \sqrt{D_n \tau_n}$, $V = D_n/L$, and D_n is the diffusion coefficient for electrons in the base.

$$f_n(\alpha) \cong -\frac{\alpha L}{\left(\alpha^2 L^2 - 1\right) \cdot \left[1 - R_0 R_d \exp\left(-2\alpha d\right)\right]} \times$$

$$\times \left\{\left[\left(S_d + V\right) \cdot \exp\left(\frac{d - x_n}{L}\right) + \left(S_d - V\right) \cdot \exp\left(\frac{-d + x_n}{L}\right)\right] \times\right.$$

$$\times \left[\exp\left(-\alpha x_n\right) + R_d \exp\left(-2\alpha d + \alpha x_n\right)\right] +$$

$$\left. + 2\left[\alpha D\left(1 - R_d\right) - S_d\left(1 + R_d\right)\right] \exp\left(-\alpha d\right)\right\} \times \tag{14}$$

$$\times \left\{\left[\left(S_d + V\right) \cdot \exp\left(\frac{d - x_n}{L}\right) - \left(S_d - V\right) \cdot \exp\left(\frac{-d + x_n}{L}\right)\right]\right\} +$$

$$+ \frac{(\alpha L)^2 \left[\exp\left(-\alpha x_n\right) - R_d \exp\left(-2\alpha d + \alpha x_n\right)\right]}{\left(\alpha^2 L^2 - 1\right) \cdot \left[1 - R_0 R_d \exp\left(-2\alpha d\right)\right]},$$

The second approximation consists in the account of recombination of electron-hole pairs being generated in the region $x_{n0} \le x \le x_n$. Here, the magnitude of collection coefficient for holes in the n^+-region was calculated for the case when the following inequality is valid

$$\Delta f_p(\alpha) = \frac{1}{I} \int_{x_{n0}}^{x_n} \frac{\Delta p(x) dx}{\tau_p(x)} << f_p(\alpha), \tag{15}$$

where $\Delta p(x)$ is the excess hole concentration in the region $x_{n0} \le x \le x_n$. In this case

$$f_p^{\bullet}(\alpha) = f_p(\alpha) - \Delta f_p(\alpha), \tag{16}$$

where

$$\Delta f_p(\alpha) = \int_{x_{n0}}^{x_n} \frac{1}{\tau_p(x)} \left\{\left[-\frac{\left(f_p(\alpha) - \exp(-\alpha x_n)\right)}{D_p N_0 / p_0 x_0} +\right.\right.$$

$$\left. + \frac{\exp(-\alpha x_n) \cdot p_0}{D_p N_0 \left(\alpha + \frac{1}{x_0}\right)}\right] \exp\left(\frac{x - x_{n0}}{x_0}\right) + \frac{f_p(\alpha) - \exp(-\alpha x_n)}{D_p / x_0} -$$

$$\left. - \frac{\exp(-\alpha x)}{D_p \left(\alpha + \frac{1}{x_0}\right)}\right] dx. \tag{17}$$

In the same approximation the expression for the hole collection coefficient in the highly doped emitter for the case when $N(x) = N_0 \operatorname{erfc}(x/x_1)$ has the following form:

$$f_p^{\bullet\bullet}(\alpha) = 1 - \exp(-\alpha x_n) -$$

$$- \frac{1}{D_p} \int_0^{x_n} \frac{\exp(-y(x))}{\tau_p(x)} \int_x^{x_n} \exp(y(t))(1-\exp(-\alpha t))dtdx\,, \qquad (18)$$

where

$$y(x) = \frac{2}{x_1\sqrt{\pi}} \int_0^x \frac{\exp(-(\frac{u}{x_1})^2)du}{1 - \frac{2}{\sqrt{\pi}} \int_0^{u/x_1} \exp(-t^2)dt} \qquad (19)$$

is the dimensionless potential (in kT/q units) existing in the emitter due to $N(x)$ gradient, $y(x_n)$ is its value at $x = x_n$, and p-n-junction depth x_n is determined from the equation $\mathrm{erfc}(x_n/x_1) = p_0/N_0$.

In the above assumptions the following relation is valid for the open circuit voltage:

$$V_{oc} = \frac{kT}{q} \cdot \ln\left(\frac{\Delta n(x_n + w_0) \cdot p_0}{n_i^2} \right), \qquad (20)$$

where $\Delta n(x_n + w_0)$ is determined as follows

$$\Delta n(x_n + w_0) = 0.2812 \cdot 10^{19} \cdot (1-m)(1-r_s) \times$$

$$\times \int_0^1 \frac{f_{1n}(\alpha(z))}{z^4 \cdot \left[\exp\left(\frac{2.207}{z} \right) - 1 \right]} dz, \qquad (21)$$

$$f_{1n}(\alpha) = \frac{\alpha L}{\left(\alpha^2 L^2 - 1\right) \cdot \left[1 - R_0 R_d \exp(-2\alpha d)\right]} \times$$

$$\times \left[(S_0 + V)(S_d + V) \cdot \exp\left(\frac{d^*}{L} \right) - (S_0 - V)(S_d - V) \cdot \exp\left(\frac{d^*}{L} \right) \right]^{-1} \times$$

$$\times \Bigg\{ \alpha L[\exp(-\alpha x_n) + R_2 \exp(-2\alpha d + \alpha x_n)] \times$$

$$\times \left[(S_d + V)\exp\left(\frac{d^*}{L} \right) - (S_d - V)\exp\left(-\frac{d^*}{L} \right) \right] + 2\exp(-\alpha d) \times$$

$$[S_d(1 + R_d) - V\alpha L(1 + R_d)] - [\exp(-\alpha x_n) + R_d \exp(-2\alpha d + \alpha x_n] \times$$

$$\times \left[(S_d + V)\exp\left(\frac{d^*}{L} \right) + (S_d - V)\exp\left(-\frac{d^*}{L} \right) \right] \Bigg\}, \qquad (22)$$

and $d^* = d - x_n$.

It should be noted that photo-generation of electron-hole pairs in the emitter is not taken into account in the equation for $\Delta n(x_n + w_0)$. Estimations show that maximum error in calculation of V_{oc} in the above approximation does not exceed 1% at $x_n \leq 10^{-4}$ cm.

The conversion efficiency of the SC with unit area can be written as follows [13]:

$$\eta = \frac{J_{sc} V_{oc}}{0.136} \left(1 - \frac{kT}{qV_{oc}} \right) \left(1 - \frac{\ln\left(\frac{qV_{oc}}{kT} \right)}{\frac{qV_{oc}}{kT}} \right) \frac{2L}{l} \cdot \tanh\left(\frac{l}{2L} \right), \qquad (23)$$

where $L = \left(\frac{q\mu_n M_0 Voc}{J_{sc}} \right)^{1/2}$, $M_0 = \int_0^{x_n} N(x)dx$, μ_n - is the electron mobility in the emitter, l is the spacing between contact grid fingers.

If the top-surface contact grid consists of wide contact strip with relative area m_1 contacting to narrow parallel fingers with relative area m_2, then next simple relation between l, m_2 and finger width l_n exist:

$$l = \frac{l_n(1 - m_2)}{m_2}. \qquad (24)$$

3. Discussion of the results

In the next analysis the following set of parameters for diffusion-type SCs was used: $N_0 \approx 10^{19}$ cm^{-3}, $p_0 \approx 10^{17}$cm^{-3}, $d \approx 300$ μm, $D_n = 25$ cm^2/s, $D_p = 3.3$ cm^2/s, $\tau_{rn} = 10^{-4}$ s, $R_0 = 0$, $R_d = 0.9$, $m_1 = 0.03$, $m_2 = 0.02$, $r_s = 0$, $x_p = 10^{-4}$ cm, $P = 5 \cdot 10^{20}$ cm^{-3}, $\mu_n = 100$ cm^2/V·s, $L_n = 0.003$ cm, $S_r = 10^3$ cm/s.

By use of the equation (1) one can determine the thickness of the emitter region Δx_n with varying concentration for given above N_0 and p_0 values: $\Delta x_n \cong 4.6\, x_0$. The minimum value of τ_{rp} according to [1] is 10^{-10} s, and that gives the possibility to determine the minimum diffusion length of holes in the emitter $L_p \approx 2 \cdot 10^{-5}$ cm. In its turn, by varying τ_{rp}, x_{n0} and x_0 values it is possible to determine maximum value of the SC conversion efficiency in frames of the used model.

The change of the collection coefficient with wavelength of incident light, as calculated for $x_0 = 10^{-5}$ and $\Delta x_n \cong 0.46$ μm, is shown in Fig. 2. Curves 1, 3, 5, 7 correspond to the

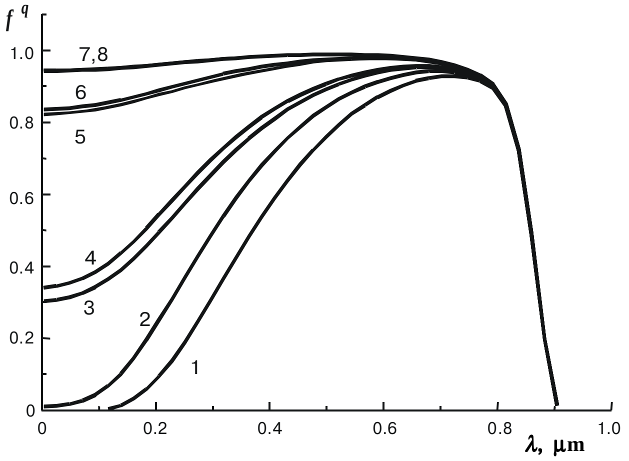

Fig.2. Conversion efficiency change with wavelength of incident light. $x_{n0} = 10^{-4}$ cm, $x_0 = 0$, $\tau_{rp} = 10^{-10}$, 10^{-9}, 10^{-8}, 10^{-7} s for curves (1, 3,5,7) correspondingly. In plotted curves (2,4,6,8) it was assumed that $x_0 = 10^{-5}$ cm, and values of τ_{rp} are the same, as for curves (1,3,5, 7).

case when recombination in the region of $N(x)$ change is neglected, and curves 2, 4, 6, 8 are plotted for the opposite case. As can be seen, the recombination in the Δx_n layer affects essentially the charge carrier collection coefficient in the range of τ_{rp} change from 10^{-9} to 10^{-10} s On the other hand, at $\tau_{rp} \geq 10^{-8}$ s the effect of recombination can be neglected. As the thickness of the Δx_n region decreases, the electron-hole recombination in it also decreases even at the minimum value of τ_{rp}, as illustrated in Fig. 3. It is seen from the figure, that at $x_0 = 2\cdot10^{-6}$ cm (corresponding to $\Delta x_n \cong 10^{-5}$ cm) the recombination in the region of $N(x)$ change has only a slight effect on the SC conversion efficiency. This effect becomes less pronounced at $\tau_{rp} \geq 10^{-9}$s

In Fig. 4 conversion efficiency change with the thickness x_{n0} of the emitter region having a constant donor concentration 10^{19} cm^{-3} is shown. Calculations were performed by use of equations (16) and (17) with (curves 2, 4, 6, 8) and without (curves 1, 3, 5, 7) taking into account electron-hole recombination in the region Δx_n. Again, as seen from the figure, an essential effect of recombination on the η value occurs at $\tau_{rp} \leq 10^{-8}$ s. In the mentioned region the shape of $\eta(x_{n0})$ curves becomes dependent on the value of τ_{rp}. In particular, at sufficiently small τ_{rp} values ($\leq 10^{-8}$ s) η increases with decreasing x_{n0} due to a lower recombination of electron-hole pairs generated in the emitter bulk. At the same time, at $\tau_{rp} \geq 10^{-8}$ s the decrease of η at low x_{n0} values is observed being related to the increase of the effective recombination rate under the contact resulting from the enhancement of diffusion supply of non-equilibrium holes.

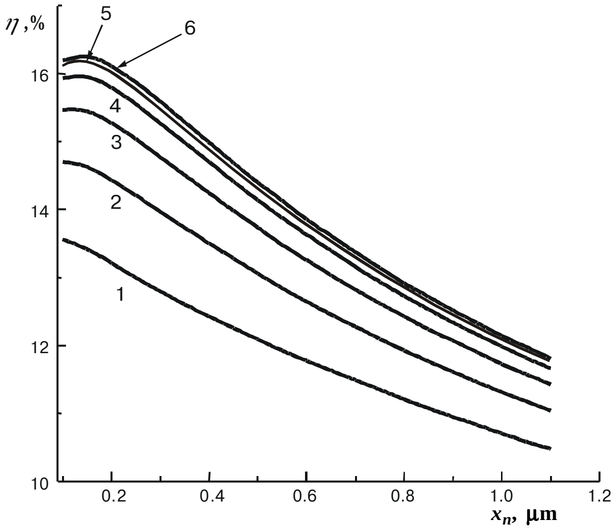

Fig.3. Conversion efficiency change with x_{n0}: $x_0 = 10^{-5}(1)$, $8\cdot10^{-6}(2)$, $6\cdot10^{-6}(3)$, $4\cdot10^{-6}(4)$, $2\cdot10^{-6}$cm(5), $\tau_{rp} = 10^{-10}$ s. Curve 6 is plotted without taking into account recombination losses in the Δx_n layer.

It should be noted that in the case of low recombination in the layer with variable donor concentration the electrical field in this layer kT/qx_0 is, at least, by an order of magnitude greater than the diffusion field kT/qL_p. For this reason the Δx_n layer can be considered as the space charge region, responsible for practically total collection of non-equilibrium charge carriers generated in this layer (see curve 8 in Fig. 2 and curve 5 in Fig. 3).

If the change in donor concentration, $N(x)$, in the Δx_n layer is determined by a classical relation of the form erfc(x/x_1), the electrical field strength change in it as:

$$E(x)=\frac{kT2}{\sqrt{\pi}qx_1}\exp\left[-\left(\frac{x}{x_1}\right)^2\right]\left[1-\frac{2}{\sqrt{\pi}}\int\limits_0^{x/x_1}\exp(-t^2)dt\right]^{-1}. \qquad (25)$$

We will consider, firstly, the situation when the criterion $E(x) > kT/qL_p$ is valid, i.e., the bulk recombination is sufficiently low in the emitter. The dependences of the conversion efficiency η on the p-n-junction depth, x_n, calculated for the above case are shown in Fig. 5. Curves (1)-(3) are plotted by use of the equation (18), and curve 4 corresponds to the case when the bulk recombination in the emitter is absent. As can be seen, η value decreases with decreasing x_n due to

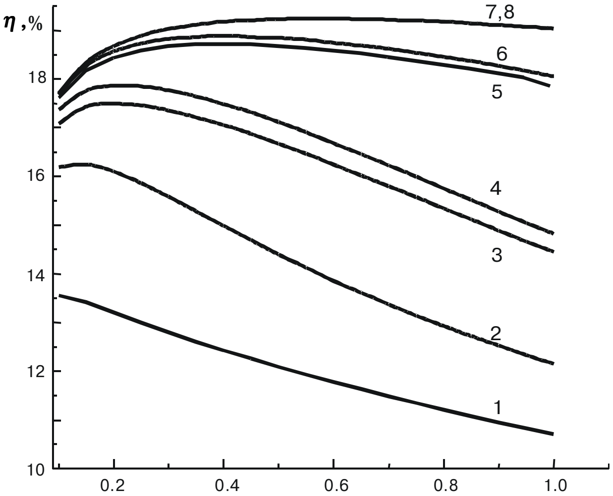

Fig.4. Dependences of η on x_{n0}. Parameters are the same as in Fig. 2.

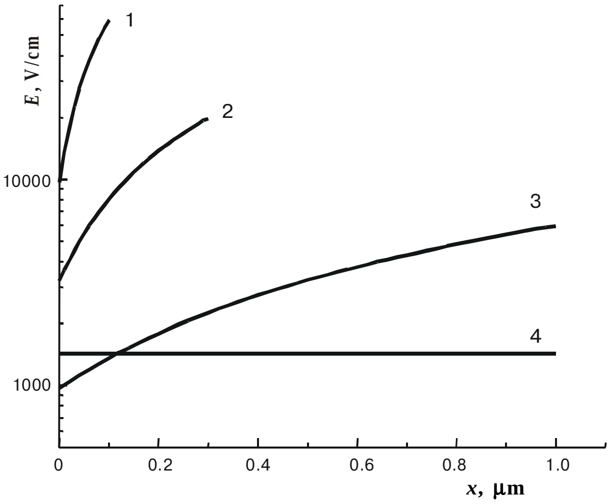

Fig.5. Conversion efficiency change with x_n in the case of classical diffusion profile: $\tau_{rp} = 10^{-8}$ (1), $3\cdot10^{-8}$ (2), 10^{-7} s (3). Curve 4 is plotted in neglecting the recombination in the n^+ – emitter.

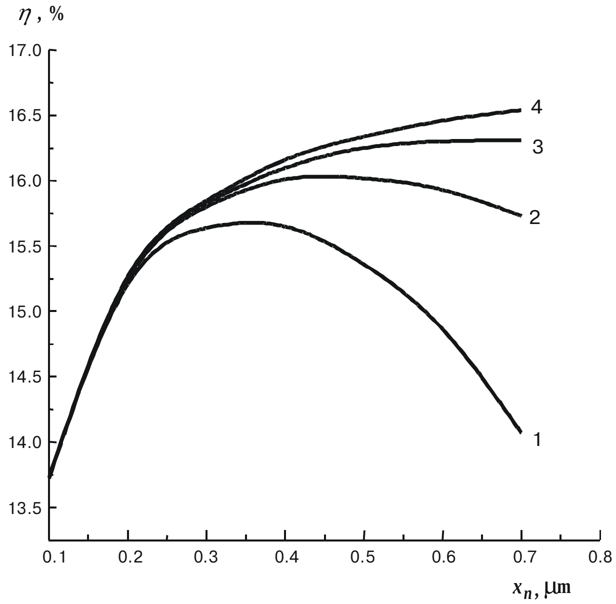

Fig.6. Electrical field distributionin the n^+ – emitter in the case of classical diffusion profile. Curves 1-3 correspond to the *p-n*-junction depths 10^{-5}, $3 \cdot 10^{-5}$ and 10^{-4} cm, respectively. Curve 4 represents the diffusion field strength calculated for $\tau_{rp} = 10^{-10}$s.

enhancing of Ohmic energy losses. On the other hand, as the Shockley-Reed-Hall lifetime, τ_{rp}, decreases, energy losses related to recombination in the n^+-emitter increase. As a rule, the conversion efficiency in the analysed conditions is less than in the case of spatially constant donor concentration. This is related to enhancement of surface recombination at the top surface resulting from the increase in diffusion supply of charge carriers through emitter.

Now the case of arbitrary relation between $E(x)$ and the diffusion field will be considered. In Fig. 6 $E(x)$ curves are plotted for different values of the *p-n*-junction depth. The value of the diffusion field strength kT/qL_p, as calculated at $\tau_{rp} = 10^{-10}$s, is also given in the figure. It is seen that $E(x)$ is essentially more high than the diffusion one only at $x_n = 10^{-5}$ cm. At $x_n = 3 \cdot 10^{-5}$ cm. At the inequality $E(x) >> kT/qL_p$ is valid only at rather large x values, and at $x_n = 10^{-4}$ the diffusion field becomes dominant at small x values indicating the presence of essential recombination in the n^+-emitter bulk. At the same time, if $\tau_{rp} \geq 10^{-8}$ s, i.e. the quality of the n^+-region is rather high, the diffusion field becomes much less than the electric field within the Δx_n region. This means that the bulk recombination in the n^+-emitter can be neglected.

Conclusions

As it follows from the above analysis, in the case of high-quality n^+-emitter when more high values of Shockley-Reed-Hall recombination lifetime in comparison with Auger recombination ones occur, the conversion efficiency of silicon SC becomes dependent, mainly, on the thickness of uniformly doped emitter region. For the used set of SC parameters appropriate quality of n^+-emitter is achieved at more high τ_{rp} values than 10^{-8} s In the case of more imperfect n^+-region, when $\tau_{rp} \approx 10^{-10}$ s, the conversion efficiency decreases with the increase of total *p-n*-junction depth, and as low as $x_n \leq 10^{-5}$ cm emitter depth is needed for obtaining acceptable η values. In the general case, the *p-n*-junction depth does not control uniquely the bulk recombination losses in the emitter region of high-efficiency silicon solar cells.

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