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Effect of excitons on photoconversion efficiency in the p^+-n-n^+- and n^+-p-p^+-structures based on single-crystalline silicon

A.P. Gorban, A.V. Sachenko, V.P. Kostylyov and N.A. Prima
Institute of Semiconductor Physics, NAS of Ukraine, 45, prospect Nauki, 03028 Kyiv, Ukraine

Abstract. We have performed theoretical simulation of the photoconversion efficiency in silicon solar cells for AM0 conditions with regard to excitonic effects. Along with known effects, we have taken into account both radiative and nonradiative exciton annihilation. They manifest themselves as square-law recombination of electron-hole pairs. It was shown that the effect of nonradiative exciton annihilation on the photoconversion efficiency is particularly profound in p^+-n-n^+-structures. In solar cells based on them the total action of all the excitonic effects leads to an about 10% decrease in the limiting value of photoconversion efficiency. At the same time for n^+-p-p^+-structures the reduction of this value due to the excitonic effects is about 5%. As a result, their limiting value of photoconversion efficiency is higher than that in p^+-n-n^+-structures.

Keywords: silicon solar cell, p^+-n-n^+-structure, n^+-p-p^+-structure, photoconversion efficiency, effect of excitons on photoconversion.

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1. Introduction

In [1-3] the excitonic effects were accounted for when considering characteristics of silicon solar cells (SC). In these papers the factors of two types have been analyzed. The first of them were those enhancing the short circuit current. These factors were related to exciton diffusion and production under irradiation with photons whose energy was below the semiconductor gap, E_g. Other factors led to a decrease in photovoltage. This resulted from a drop in concentration of the excess electron-hole pairs due to the exciton generation.

The authors of [4,5] considered the excitonic effects in both radiative and Auger recombination processes. These effects reduced the photoconversion efficiency. In [6] it was shown that, in addition to the above effects, one more effect exists that is related to the nonradiative annihilation of excitons and is of particular essence in n-type materials. This effect (making itself evident in the fact that for p^+-n-n^+-structures the square-law recombination constant, A, grows) can be easily simulated theoretically because a correlation exists between the Shockley-Reed-Hall value of charge carrier lifetime, τ_r, and A. The latter fact has been found in [6] from an analysis of experimental data.

In this paper we shall take into account all the above effects (except that related to the exciton generation under irradiation with photons whose energy is less than E_g) when considering theoretically the photoconversion efficiency in the p^+-n-n^+- and n^+-p-p^+-structures based on single-crystalline silicon.

2. Statement of the problem

Our calculation of the photoconversion efficiency will be based on the approach developed by us in [7-10]. For the sake of simplicity, we shall restrict our further consideration to a model in which the charge carrier concentration is distributed in a stepwise way over heavily doped n^+- and p^+-regions. For definiteness sake, we shall consider SCs with n-type base. (The case of SCs with p-type base will be discussed in its own right.)

The expressions for the photoconversion efficiency were obtained analytically for the following two limiting cases: (i) the base thickness is smaller than the diffusion length of electron-hole pairs, and no restrictions exist on the ratio between the concentration of excess electron-hole pairs and equilibrium concentration of majority charge carriers in the base; (ii) the concentration of excess electron-hole pairs is small as compared to the equilibrium concentration of majority charge carriers, and no restrictions exist on the ratio between the base thickness and charge carrier diffusion length in the base.

According to the results of [6], the effective charge carrier lifetime in the base bulk will be taken as

$$\frac{1}{\tau_p} = \frac{1}{\tau_{rp}} + A(n_0 + \Delta n) + C_n(n_0 + \Delta n)^2 + C_p(n_0 + \Delta n)\Delta n \, . \tag{1}$$

Here τ_{rp} is the Shockley-Reed-Hall value of recombination lifetime; n_0 (Dn) is the equilibrium (excess) electron concentration in the base;

$$C_n(n_0 + \Delta n) \cong (2.8 \cdot 10^{-31} + \frac{2.5 \cdot 10^{-22}}{(n_0 + \Delta n)^{1/2}}) \text{ cm}^6\text{/s};$$

$$C_p \cong 10^{-31} \text{ cm}^6\text{/s}. \tag{2}$$

The contributions to the square-law recombination constant, A, come from the interband recombination, Auger recombination (that involve impurities) and exciton annihilation (both radiative and nonradiative) that also proceeds in accordance to Auger mechanism involving impurities.

Let us consider that the minority charge carrier lifetimes in heavily doped p^+- and n^+-regions are determined by Auger recombination and are

$$\tau_n{}^+ = (C_p{}^+ P^2)^{-1}, \tau_p{}^+ = (C_n{}^+ N^2)^{-1}, \tag{3}$$

respectively. Here N (P) is the electron (hole) concentration in n^+- and p^+-regions. It should be noted that the expression for C_n might be applied also to determine $C_n{}^+$ after substitution $n_0 + \Delta n \rightarrow N$.

3. Theoretical calculations

According to [7], the effective recombination rate at the front (i.e., illuminated) surface, S_0, may be written down as

$$S_0 = r_0(1 + \Delta n(x = 0)/n_0) \, , \tag{4}$$

where

Here $V_n = D_n/L_n$, D_n and L_n are the electron diffusion parameters (velocity, coefficient and length, respectively) in the heavily doped p^+-region; N_v is the effective density of state in the semiconductor valence band; $\Delta E_g^{(p^+)}$ is the silicon gap decrease (in units of kT) in the p^+-region; Z_p is determined from the equation

$$P = N_v F_{1/2}(Z_p) \, . \tag{6}$$

Here $F_{1/2}(Z_p)$ is the Fermi-Dirac integral of the order of 1/2; S_{nm} (S_r) is the "true" recombination rate for electrons at the semiconductor-metal (semiconductor-insulator) interface; x_p is the p^+-region thickness; m is the ratio between the area of the front contact grid and that of SC surface; Δn ($x = 0$) is the excess concentration of electron-hole pairs under the front contact.

By analogy with expressions (4) and (5), the recombination rate at the back surface, S_d, is

$$S_d = r_d(1 + \Delta n(x = d)/n_0 \, , \tag{7}$$

where

$$r_d = V_p \frac{n_0}{N_c} \exp\left(\Delta E_g^{(n^+)} - Z_n\right) \times$$

$$\times \left[\frac{S_{pm} \cosh\left(\frac{x_n}{L_p}\right) + V_p \sinh\left(\frac{x_n}{L_p}\right)}{S_{pm} \sinh\left(\frac{x_n}{L_p}\right) + V_p \cosh\left(\frac{x_n}{L_p}\right)} \right] . \tag{8}$$

Here $V_p = D_p^+ / L_p$, D_p^+ and L_p are the hole diffusion parameters (velocity, coefficient and length, respectively) in the n^+-region; N_c is the effective density of state in the silicon conduction band; $\Delta E_g^{(n^+)}$ is the silicon gap decrease (in units of kT) in the n^+-region; Z_n is determined from the equation

$$N = N_c F_{1/2}(Z_n) \, . \tag{9}$$

Here S_{pm} is the "true" recombination rate for holes at the semiconductor-metal interface; x_n is the n^+-region thickness; Δn ($x = d$) is the excess concentration of electron-hole pairs under the back contact.

$$r_0 = V_p \frac{n_0}{N_v} e^{\Delta E_g^{(p^+)} - Z_p} \left[\left(S_{nm} \cosh\left(\frac{x_p}{L_n}\right) + V_n \sinh\left(\frac{x_p}{L_n}\right) \right) m \Big/ \left(S_{nm} \sinh\left(\frac{x_p}{L_n}\right) + V_n \cosh\left(\frac{x_p}{L_n}\right) \right) + \right.$$

$$\left. + \left(S_r \cosh\left(\frac{x_p}{L_n}\right) + V_n \sinh\left(\frac{x_p}{L_n}\right) \right) (1 - m) \Big/ \left(S_r \sinh\left(\frac{x_p}{L_n}\right) + V_n \cosh\left(\frac{x_p}{L_n}\right) \right) \right] . \tag{5}$$

It should be noted that the first term in brackets (expression (5)) relates to the recombination under contacts, while the second one relates to the recombination in the intercontact gaps. Along with the surface recombination, that in the bulk of the heavily doped p^+-region is taken into consideration in expressions (4) and (5).

According to the model proposed in [7], the electron-hole generation function is

$$f(\alpha,x) \cong \alpha I\sqrt{R_0}\cdot\frac{\left(\exp(-\alpha x)+R_2R_d\exp(-2\alpha d+\alpha x)\right)}{1-R_0R_1R_2R_d\exp(-2\alpha d)}. \tag{10}$$

Here I is the intensity of monochromatic illumination; $R_0=\exp\left(-2\cdot10^{-39}P^2\lambda^{7/2}x_p\right)$ is the coefficient of damping due to light absorption by free charge carriers in the p^+-region; $R_d=\exp\left(-3.6\cdot10^{-39}N^2\lambda^{7/2}x_n\right)$ is the same as R_0 but in the n^+-region; λ is the illuminating light wavelength (in units of mm); R_1 (R_2) is the reflection coefficient for light that is incident on the front (back) surface from the sample bulk.

When writing down the above expressions for R_0 and R_d, it was assumed that Born approximation is valid for light absorption in our case when the charge carriers are predominantly scattered on the charged impurities and there is no compensation in the heavily doped regions. The situation when $R_1 = R_2 = 1$ corresponds to the case of complete light absorption in semiconductor. Such a case may be realized in textured or profiled SC surfaces.

If, for AM0 conditions, the spectrum of solar radiation is approximated by that of the ideal radiator at a temperature T_c = 5800 K, then the SC short-circuit current density (in units of A/cm^2), J_{sc}, at an ambient temperature of 300 K is given by the following expression:

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

Here r_s is the coefficient of light reflection from the SC front surface; $z=\lambda/\lambda_x$ (λ_x is the long-wave limit for inner photoeffect in silicon; $f_n(\alpha)$ and $f_p(\alpha)$ are the collection coefficient spectral dependencies for electrons in the p^+-region and holes in the n-region, respectively; $\alpha(z)$ is the spectral dependence of light absorption coefficient (its analytical expression is given in [11]).

Using the conventional procedure for calculation of the diffusion flows of electrons (at the p^+-region boundary) and holes (at the $x = x_p$ plane), one obtains:

$$f_n(\alpha)=\frac{\alpha L_n\sqrt{R_0}}{1+\alpha L_n}\times\left[\frac{S_r\left(1-\exp\left(-\alpha x_p+\frac{x_p}{L_n}\right)\right)+V_n\left(\alpha L_n-\exp\left(-\alpha x_p+\frac{x_p}{L_n}\right)\right)}{\left(\alpha L_n-1\right)\left[S_r\sinh\left(\frac{x_p}{Ln}\right)+V_p\cosh\left(\frac{x_p}{L_n}\right)\right]}-\exp\left(-\alpha x_p\right)\right], \tag{12}$$

$$\begin{aligned}f_p(\alpha)\cong{}&-\frac{\alpha L\sqrt{R_0}}{\left(\alpha^2L^2-1\right)\left[1-R_0R_1R_2R_d\exp(-2\alpha d)\right]}\times\\&\times\left\{\left[\left(r_d+V\right)\exp\left(\frac{d-x_p}{L}\right)+\left(r_d-V\right)\exp\left(\frac{-d+\left(x_p\right)}{L}\right)\right]\times\right.\\&\times\left[\exp\left(-\alpha\left(x_p\right)\right)+R_2R_d\exp\left(-2\alpha d+\alpha\left(x_p\right)\right)\right]+\\&\left.+2\left[\alpha D\left(1-R_2R_d\right)-r_d\left(1+R_2R_d\right)\right]\exp\left(-\alpha d\right)\right\}\times\\&\times\left[\left(r_d+V\right)\exp\left(\frac{d-\left(x_p\right)}{L}\right)-\left(r_d-V\right)\exp\left(\frac{d-\left(x_p\right)}{L}\right)\right]^{-1}+\\&+\frac{\sqrt{R_0}\left(\alpha L\right)^2\left[\exp\left(-\alpha\left(x_p\right)\right)-R_2R_d\exp\left(-2\alpha d+\alpha\left(x_p\right)\right)\right]}{\left(\alpha^2L^2-1\right)\left[1-R_0R_1R_2R_d\exp(-2\alpha d)\right]},\end{aligned} \tag{13}$$

Here $L=\sqrt{D_p\tau_p}$, $V=D_p/L$, D_p is the hole diffusion coefficient in the base.

Let us next calculate the photoconversion efficiency, $\eta(P,x_p,N,x_n,n_0,d)$. To do this, we shall at first determine the open circuit voltage, V_{oc}. It is a sum of the voltage drops on two contacts (front and back) at illumination:

$$V_{oc}=\frac{kT}{e}\cdot\ln\left[\frac{\Delta n(x=0)}{p_0}\cdot\left(1+\frac{\Delta n(x=d)}{n_0}\right)\right]. \tag{14}$$

In the limiting case of thin base the excess electron-hole pair concentration in the base bulk is constant; therefore

$$\Delta n=-\frac{n_0}{2}+\left[\frac{n_0^2}{4}+n_i^2\exp\left(\frac{eV_{oc}}{kT}\right)\right]^{1/2}. \tag{15}$$

Taking, as it usually is, that (with a load) the results from forward bias and illumination are equivalent, one may write down the following expression for the SC I-V curve:

$$\begin{aligned}J(V)=J_{SC}-q\left[d\Delta n^*/\tau_n(\Delta n^*)-\right.\\\left.-S_0(\Delta n^*)\Delta n^*-S_d(\Delta n^*)\Delta n^*\right].\end{aligned} \tag{16}$$

Δn^* can be determined from expression (15) after substitution of V for V_{oc}. Using the condition that the takeoff power, $P_m = J(V_m)V_m$, is maximum, one obtains a transcendental equation for determination of V_m, and next the photoconversion efficiency may be found. Using the results of [12], the efficiency of SC of unit area may be written down as

$$\eta = \frac{J(V_m)V_m^*}{0.136}\frac{2L}{l}\tanh\frac{l}{2L} \tag{17}$$

Here

$$V^*{}_m = V_m - 2\frac{kT}{q}\times$$
$$\times\ln\left(1+\frac{n_0+\Delta n_m}{n^*\exp\left(\frac{E_x}{kT}\right)\exp\left[-\frac{E_x}{kT}\left(1-(\frac{n_0}{10^{18}})^{0.5}\right)^2\right]}\right)+$$
$$+\frac{kT}{q}\ln\left\{1+\frac{n_0}{n^*\exp\left(\frac{E_x}{kT}\right)\exp\left[-\frac{E_x}{kT}\left(1-(\frac{n_0}{10^{18}})^{0.5}\right)^2\right]}\right\}, \tag{18}$$

thus taking into account the thermodynamic effect of excitonic action (that has been considered in [1-3]) on photovoltage in the maximum takeoff power mode; n^* is the parameter determined in [1]; E_x is the exciton binding energy when shielding is absent; $L = (\frac{\mu_p P\cdot x_p\cdot kT}{J_{sc}-J(Vm)})^{1/2}$, μ_p is the hole mobility in the p^+-region; l is the spacing between the contact grid lines. In our calculations we took, according to [1], that $E_x \cong 15$ meV, $n^*\exp(E_x/kT) \cong 1.43\times10^{18}$ cm^{-3}.

Now we shall specify a contact grid. Let it be a set of broad contact buses (that short the system) and narrow parallel strips. The relative area of buses is m_1, that of strips is m_2, and their total area is m. Then one can get the following simple expression that relates m_2, the strip thickness, l_n, and interstrip spacing, l:

$$l = \frac{l_n(1-m_2)}{m_2}. \tag{19}$$

When $\Delta n << n_0$, then the photoconversion efficiency is calculated in another way. Now V_{oc} is determined by the first factor in brackets in expression (14), $\frac{\Delta n(x=0)}{p_0}$, only. According to the approach used in [8], for the AM0 conditions we have:

$$\Delta n(x=0) = 0.2812\cdot10^{19}(1-m)(1-r_s)\times$$
$$\times\int_0^1\frac{f_{1p}(\alpha(z))}{z^4\left[\exp\left(\frac{2.207}{z}\right)-1\right]}dz \tag{20}$$

Here

$$f_{1p}(\alpha) = \frac{\alpha L\sqrt{R_0}}{(\alpha^2L^2-1)[1-R_0R_1R_2R_d\exp(-2\alpha d)]}\times$$
$$\times\left[(r_0+V)(r_d+V)\exp\left(\frac{d}{L}\right)-(r_0-V)(r_d-V)\exp\left(\frac{d}{L}\right)\right]^{-1}\times$$
$$\times\{\alpha L[\exp(-\alpha(x_p))+R_2R_d\exp(-2\alpha d+\alpha(x_p))]\times$$
$$\times\left[(r_d+V)\exp\left(\frac{d}{L}\right)-(r_d-V)\exp\left(-\frac{d}{L}\right)\right]+$$
$$+2\exp(-\alpha d)[r_d(1+R_2R_d)-V\alpha L(1+R_2R_d)]-$$
$$-[\exp(-\alpha(x_p))+R_dR_2\exp(-2\alpha d+\alpha(x_p))]\times$$
$$\times\left[(r_d+V)\exp\left(\frac{d}{L}\right)+(r_d-V)\exp\left(-\frac{d}{L}\right)\right]\}. \tag{21}$$

It should be noted that the photoproduction of electron-hole pairs in the n^+-region is not accounted for in the expression for Δn ($x = 0$). The estimated maximum error (due to the use of the above approximation) made when calculating V_{oc} does not exceed 0.3% at $x_p \le 10^{-4}$ cm.

In the second limiting case the photoconversion efficiency for SC of unit area may be presented as

$$\eta = \frac{J_{sc}V^*{}_{oc}}{0.136}\left(1-\frac{kT}{qV^*{}_{oc}}\right)\times$$
$$\times\left(1-\frac{\ln\left(\frac{qV^*{}_{oc}}{kT}\right)}{\frac{qV^*{}_{oc}}{kT}}\right)\frac{2L}{l}\cdot\tanh\left(\frac{l}{2L}\right), \tag{22}$$

where

$$V_{oc}^{*} = V_{oc} - \frac{kT}{q} \times$$
$$\times \ln\left(1 + \frac{n_0}{n^{*} \exp\left(\frac{E_x}{kT}\right) \exp\left[-\frac{E_x}{kT}\left(1 - \left(\frac{n_0}{10^{18}}\right)^{0.5}\right)^{2}\right]}\right).$$

The above expressions enable one to calculate, in the two limiting cases, the photoconversion efficiency for silicon SCs with *n*-base in the AM0 conditions as a function of the following quantities: (i) the spacing between the contact grid lines, (ii) doping levels and thicknesses of the base, p^+- and n^+-regions. To apply the above expressions to SCs with *p*-base, one should make the following substitutions: $n_0 \to p_0$, $P \to N$, $N \to P$, $x_n \to x_p$, $x_p \to x_n$, $D_p^+ \to D_n^+$, $\mu_p \to \mu_n$, $C_n(n_0 + \Delta n) \to C_n(\Delta n)$.

When performing actual calculations, we used the following numerical values: $S_{pm} \cong S_{nm} = 2.5 \cdot 10^6$ cm/s; $S_r = 10^3$ cm/s; $D^+{}_p = 3.3$ cm²/s [13]; $D^+{}_n = 7$ cm²/s [14]. For $\Delta E_p(P)$ and $\Delta E_n(N)$ the following empirical relations were used [15]: $\Delta E_g^{n^+}(N) = 0.0124 \cdot \left(\frac{N}{n_i}\right)^{0.25}$, $\Delta E_g^{p^+}(P) = 0.0124 \cdot \left(\frac{P}{n_i}\right)^{0.25}$.

4. Discussion of results

The approach corresponding to the first limiting case is valid at rather big values of Shockley-Reed-Hall lifetimes. It enables to estimate the limiting photoconversion efficiency for silicon SCs in the AM0 conditions. When applying this approach for *n*-type materials, we shall use the record values of Shockley-Reed-Hall lifetimes from [16]. The corresponding *A* values have been determined by us in [6] from comparison between the experimental and theoretical $\tau_p(\Delta n)$ dependencies. Let us consider (according to results obtained in [6]) that, when in a high-quality *p*-type material one can obtain the same Shockley-Reed-Hall lifetime values as in an *n*-type material, the time of exciton annihilation in them is determined by that of radiative annihilation. This gives $A = 2.5 \cdot 10^{-15}$ cm³/s. Besides, in actual calculations we shall take $R_1 = R_2 = 1$, $d = 100$ µm; $m = 0.01$; $S_0 = S_d = 0$. The effect of layer resistance of the front contact on the photoconversion efficiency will not be taken into account. This means that the product $\frac{2L}{l} \cdot \tanh(\frac{l}{2L})$ in expression (1) is taken to be equal to 1.

Shown in Fig. 1 is the open circuit voltage as a function of the base doping level. The curves 1 and 2 are plotted, without accounting for excitonic effects, for the case when $A = 1.5 \times 10^{-15}$cm³/s, and $C_n = 2.8 \times 10^{-31}$cm⁶/s. One can see from Fig. 1 that for *n*-type base the $V_{oc}(n_0)$ curves are monotone. The open circuit voltage, V_{oc}, dopes not depend on the doping level at $n_0 > 10^{16}$ cm^{-3} and goes down at $n_0 > 10^{16}$ cm^{-3} because both the square-law and Auger recombination become efficient. Contrary to this, the $V_{oc}(p_0)$ curves for *p*-type base are nonmonotonous and have a peak at $p_0 \approx 10^{17}$cm^{-3}. They differ qualitatively from the corresponding curves given in [17] that have no peak. Appearance of a peak in our case is related to the realization of a linear injection level at $p_0 \approx 10^{16}$cm^{-3}, so that a contribution from Auger recombination of electrons decreases with p_0 over a rather narrow range of p_0 changes.

For *p*-type base the V_{oc} values are very close when the Shockley-Reed-Hall lifetime values differ by a factor of four. At the same time the open circuit voltage in the p^+-*n*-n^+-structures drops substantially when the Shockley-Reed-Hall lifetime decreases from $3.8 \cdot 10^{-2}$ to $9 \cdot 10^{-3}$ s. This is related to the appearance of the channel of exciton nonradiative annihilation; as a result, the constant *A* increases by an order of magnitude.

Shown in Fig. 2 are the limiting photoconversion efficiency *vs* base doping level curves plotted for the same parameters. In particular, the curves 1 and 2 are plotted for the same parameters as are for curves 1 and 2 in Fig. 1 (i.e., the excitonic effect is not accounted for). From comparison between the Figs 1 and 2 one can see that the photoconversion efficiency curves are similar to the $V_{oc}(n_0)$ curves. From Fig. 2 one can see that, at the same Shockley-Reed-Hall lifetime values, the limiting photoconversion efficiency in n^+-*p*-p^+-structures is higher than

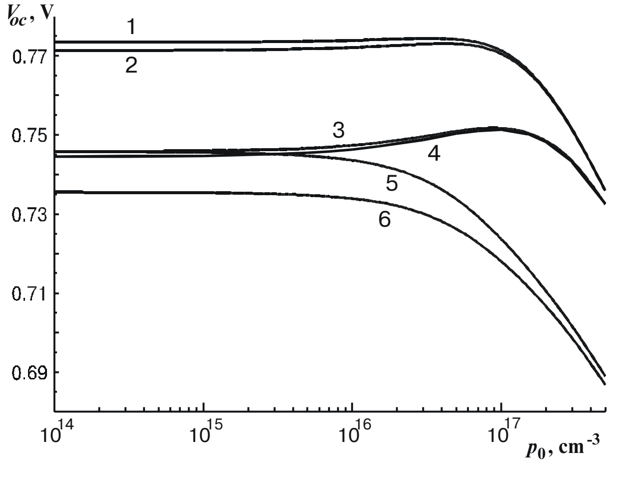

Fig. 1. Theoretical dependencies of the open circuite voltage value on the solar cell (SC) base doping level for the *p*-(1-4) and *n*-(5,6) semiconductor. SC parameters: $\tau_r = 3.8 \cdot 10^{-2}$ (1,3,5) and $9 \cdot 10^{-3}$ s (2,4,6), $A = 1.5 \cdot 10^{-15}$ (1,2), $2.5 \cdot 10^{-15}$ (3,4,5) and $3 \cdot 10^{-14}$ cm³·s⁻¹ (6).

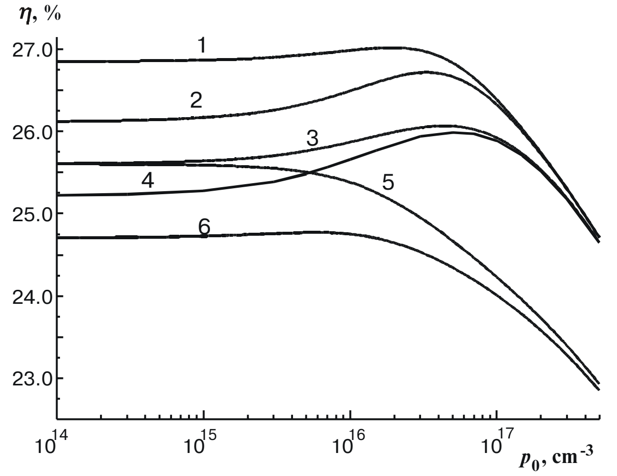

Fig. 2. Theoretical dependencies of the efficiency on the SC base doping level for the *p*-(1-4) and *n*-(5,6) semiconductor. SC parameters is the same as Fig. 1.

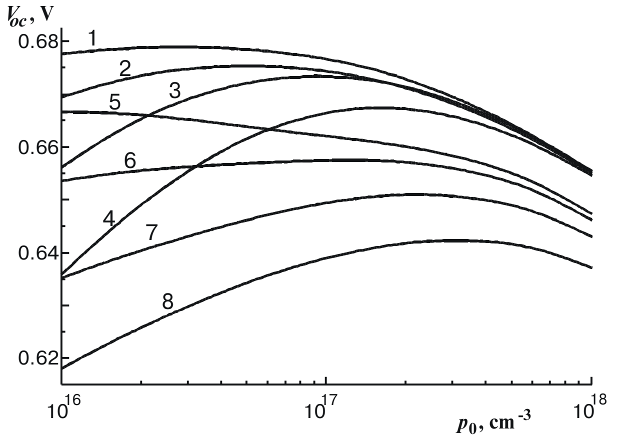

Fig.3. Theoretical dependencies of the open circuite voltage value on the solar cell (SC) base doping level for the p-(1-4) and n-(5,8) semiconductor. SC parameters: τ_r = 7·10^{-3} (1,5), 2·10^{-3} (2,6), 6·10^{-4} (3,7), and 2·10^{-4} s (4,8), A = 3·10^{-15} (1,3), 10^{-14} (2), 1.3·10^{-14} (4), 3.9·10^{-14} (5), 1.4·10^{-13} (6,8), and 4.5·10^{-13} cm^3·s^{-1} (7).

that in p^+-n-n^+-structures. This in no way is related to the lower diffusion coefficient for holes. The maximum values of the limiting photoconversion efficiency in n^+-p-p^+- and p^+-n-n^+-structures are realized at different doping levels. In the first case this doping level is ≈10^{17}cm^{-3}, while for the latter structures it is ≤10^{16}cm^{-3}. And when the excitonic effects are taken into account, then the limiting photoconversion efficiency values for the AM0 conditions are about 5% (in n^+-p-p^+-structures) and about 10% (in p^+-n-n^+ -structures) lower than those without account for these effects [7].

When analyzing the second limiting case, the following parameter values were used: d = 300 μm; D_n = 25 cm^2/s; D_p = 7 cm^2/s; R_1 = 0; R_2 = 0.9; m_1 = 0.03; m_2 = 0.02; r_s = 0; l = 0.003 cm; $\mu_{p(n)}$ = 10^2 cm^2/Vs. In this analysis it was also taken that the thicknesses of both front and back heavily doped regions are 1 mm and the charge carrier concentrations in these regions are 10^{19} and 5·10^{20} cm^{-3}, respectively.

Shown in Fig. 3 are the open circuit voltage vs the base doping level curves plotted for the above parameter values. The bulk recombination parameters that corresponded to the experimentally measured lifetimes in the p-type material served as the basis for calculation. For the n-type base the Shockley-Reed-Hall lifetime values were taken the same as for the p-type base. The parameter A has been determined using a correlation between τ_{rp} and A values (obtained in [6]) for the case $\tau_{rp}A$ = 2.7× ×10^{-16} cm^{-3}. As in the first case, the V_{oc} vs doping level curves for SC with p-type base have a peak at p_0≈10^{17}cm^{-3}; the V_{oc} magnitudes are bigger than those in the case of SC with n-type base.

The V_{oc} vs doping level curves for SC with n-type base are more diversified than those for thin base. At big Shockley-Reed-Hall lifetime values V_{oc} decreases with n_0. As τ_{rp} goes down, a peak on the V_{oc} vs n_0 curves appears that shifts toward bigger n_0 values. One can explain all the above facts by taking into account that (i) as τ_{rp} decreases, the case of thin base is transforming to that of thick base and (ii) a correlation between τ_{rp} and A exists in the n-type base. Indeed, in the limiting case when there is no surface recombination the V_{oc} value is determined by the following expression:

$$V_{oc} \cong \frac{kT}{q}\ln\left(\frac{J_{sc}n_0}{qn_i^2\,\frac{D_p^*}{L}\tanh\frac{d}{L}}\right) - \frac{kT}{q}\ln\left\{1+\frac{n_0}{n^*\exp\left(\frac{E_x}{kT}\right)\exp\left[-\frac{E_x}{kT}\left(1-\frac{n_0^{1/2}}{10^9}\right)^2\right]}\right\}. \quad (23)$$

Here

$$L=\sqrt{D_p{}^*\tau_p}\,,\; D_p{}^* = D_p + D_x\frac{n_o}{n^*}\ ,$$

$$\tau_p{}^{-1} = \frac{1}{\tau_{rp}}(1+2.7\cdot 10^{-16}n_0)+C_n(n_0)n_0{}^2)\ ; \quad (24)$$

the exciton diffusion coefficient D_x = 17 cm^2/s.

Taking into account (24), one can write down the following expressions for V_{oc} in the limiting cases of thin and thick base:

$$V_{oc} \cong \frac{kT}{q}\ln\left(\frac{J_{sc}n_0}{qn_i^2 d\left[\frac{1}{\tau_{rp}}(1+2.7\cdot 10^{-16}n_0)+C_n n_0^2\right]}\right)$$

$$-\frac{kT}{q}\ln\left\{1+\frac{n_0}{n^*\exp\left(\frac{E_x}{kT}\right)\exp\left[-\frac{E_x}{kT}\left(1-\frac{n_0^{1/2}}{10^9}\right)^2\right]}\right\}; \quad (25)$$

$$V_{oc} \cong \frac{kT}{q}\times$$

$$\times\ln\left(\frac{J_{sc}n_0}{qn_i^2\sqrt{D_p^*\left(\frac{1}{\tau_{rp}}(1+2.7\cdot 10^{-16}n_0)+C_n(n_0)n_0^2\right)}}\right)-$$

$$-\frac{kT}{q}\ln\left\{1+\frac{n_0}{n^*\exp\left(\frac{E_x}{kT}\right)\exp\left[-0.567\left(1-\frac{n_0^{1/2}}{10^9}\right)^2\right]}\right\}. \quad (26)$$

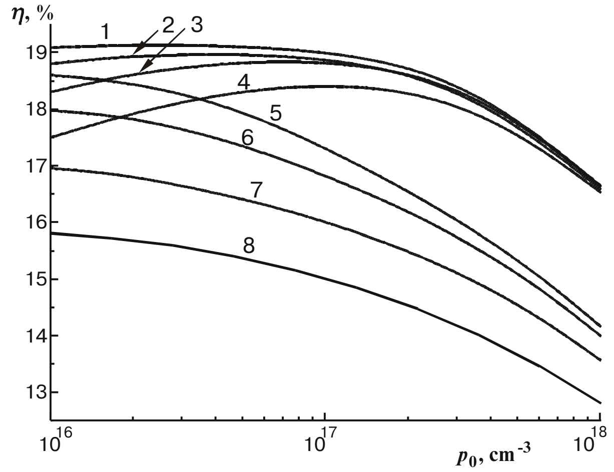

Fig. 4. Theoretical dependencies of the efficiency on the SC base doping level for the p-(1-4) and n-(5,6) semiconductor. SC parameters is the same as Fig.3.

One can see from expression (25) that in the case of thin base V_{oc} decreases at $n_0 \geq 10^{16}$ cm^{-3}. And in the case of thick base V_{oc} continues to grow as long as the dependence $C_n(n_0)$ is of essence. The smaller τ_{rn}, the longer the V_{oc} growth continues.

The photoconversion efficiency vs base doping level curves for n-Si are similar to the concentration dependencies of V_{oc} (see Fig. 4). At the same time the photoconversion efficiency monotonically decreases with n_0 in the case of n-type base (see Fig. 4, curves 5-8).

Conclusions

We have shown that the exciton nonradiative annihilation (that occurs according to Auger mechanism involving deep-lying impurity and manifests itself as square-law recombination of electron-hole pairs) leads to a decrease in both the open circuit voltage and photo-conversion efficiency in the p^+-n-n^+-structures, as compared to the n^+-p-p^+-structures (where this exciton nonradiative annihilation can be minimized). The total action of all the excitonic effects on the photoconversion efficiency in the p^+-n-n^+-structures is about twice as big as that in the n^+-p-p^+-structures.

It was also shown that the highest value of the photoconversion efficiency in the p^+-n-n^+-structures could be achieved at the base doping level $n_0 < 10^{16}$ cm^{-3}, contrary to the case of n^+-p-p^+-structures where the optimum base doping level is $p_0 \approx 10^{17}$ cm^{-3}.

References

1. D.E. Kane, R.M. Swanson, The effect of excitons on apparent band gap narrowing and transport in semiconductors // *J. Appl. Phys.* **73**(3), pp. 1193-1197 (1993).
2. R. Corkish, Daniel S.-P. Chan, M.A. Green // *J. Appl. Phys.* **79**, p. 195 (1993).
3. M.A. Green, Excitons in silicon solar cells: room temperature distributions and flows, in *2nd World Conference and Exhibition on Photovoltaic Solar Energy Conversion*, 6-10 July 1998, Vienna, Austria, pp. 74-76.
4. M. Ruff, M. Fick, R. Lindner, U. Rossler, R. Heilig, The spectral distribution of the intrinsic radiative recombination in silicon // *J. Appl. Phys.* **74**(1), pp. 267-274 (1993).
5. A. Hangleiter, R. Hacker, Enhancement of band-to-band Auger recombination by electron-hole correlations // *Phys. Rev. Lett.* **65**(2), pp. 215-218 (1990).
6. A.V. Sachenko, A.P. Gorban, V.P. Kostylyov, Exciton-enhanced recombination in silicon at high concentrations of charge carriers // *Semiconductor Physics, Quantum Electronics & Optoelectronics*, **3**(1), (2000).
7. A.V. Sachenko, N.A. Prima, A.P. Gorban, Limiting efficiency of silicon solar cells with n^+-p-p^+-structure (in Russian) // *Optoelektronika i Poluprovodnikovaya Tekhnika* N **34**, pp. 41-46 (1999).
8. A.P. Gorban, V.P. Kostylyov, A.V. Sachenko, The optimization of n^+-p-p^+-silicon solar cells parameters. Theoretical relations (in Russian) // *Optoelektronika i Poluprovodnikovaya Tekhnika* N **34**, pp. 63-71 (1999).
9. A.V. Sachenko, N.A. Prima, A.P. Gorban, Conversion efficiency in silicon solar cells with spatially nonuniform doping // *Semiconductor Physics, Quantum Electronics & Optoelectronics* **2**(3), pp. 32-37 (1999).

10. A.P. Gorban, V.P. Kostylyov, A.V. Sachenko, Effect of emitter properties on the conversion efficiency of silicon solar cells // *Semiconductor Physics*, *Quantum Electronics* & *Optoelectronics* **2**(3), pp. 26-31 (1999).
11. K. Rajkanan, R. Singh, J. Shewchun, Absorption coefficient of silicon for solar cell // *Sol. St. Electron*. 22(9), pp. 793-796 (1979)
12. A.V. Sachenko, A.P. Gorban, On the collection of photocurrents in solar cells with contact grid // *Semiconductor Physics*, *Quantum Electronics* & *Optoelectronics* **2**(2). pp. 42-44 (1999).
13. C.H. Wang, K. Misiacos, A. Neugroschel, Minority diffusion length in heavily doped silicon // *J. Appl. Phys*. **54**(22), pp. 2233-2234(1989).
14. P.M. Dunbar, J.R. Hauser, A study of efficiency in low resistivity silicon solar cells // *Sol. St. Electron*. **19**(2), pp. 95-102 (1976).
15. E.K. Banghart, J.L. Gray, R.J. Schwartz, The effects of high level injection on the performance of high intensity, high efficiency silicon solar cells, in *20th IEEE Photovoltaic Spec. Conf., Las Vegas, September 26-30, 1988*, 1, pp.717-722, Conf. Rec.–New York (1988).
16. E. Yablonovitch, T. Gmitter, Auger recombination in silicon at low carrier densities // *Appl. Phys. Lett*. 49, p. 587 (1986).
17. P. Campbell, M.A. Green, Efficiency limits for silicon concentrator solar cells, in *Proc. IEEE 18th Photovoltaic Spec. Conf. (Las Vegas, NV), Oct. 1985*, pp. 430-434 (1985).