PHOTOELECTRIC CHARACTERISTICS OF SILICON PHOTOSENSITIVE STRUCTURES WITH NON-OHMIC REAR CONTACTS

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Detailed studies of the dependences of open-circuit voltage on the irradiance level, $V_{OC}(P_L)$, the spectral dependences of short-circuit current, $I_{SC}(\lambda)$, and the spectral dependences of open-circuit voltage, $V_{OC}(\lambda)$, have been carried out for silicon photosensitive structures with nonmonotonous (possessing a maximum) dependence $V_{OC}(P_L)$. The peculiarities in the P_L-dependences were found to result from non-Ohmic properties of a rear contact in the investigated structures. The proposed model of the rear contact influence on the processes of generation, recombination, and collection of charge carriers in silicon photosensitive structures provides a quantitative agreement between theoretical and experimental dependences in a wide irradiance range. It has been demonstrated that the measurements of $V_{OC}(P_L)$ and $I_{SC}(P_L)$ dependences should be used as an additional method for the characterization of photosensitive structures, which allows one to get an additional important information concerning the properties of their rear contacts.

1. Introduction

It has been revealed in works [1, 2] that the dependences of the open-circuit voltage V_{OC} on the surface irradiance P_L of silicon solar cells (SCs) belonging to the diffused field-effect type turn out nonmonotonic in some cases, i.e. as the irradiance P_L grows, the voltage V_{OC} firstly increases, passes through a maximum, and then starts to decrease. It was associated with a non-Ohmic character of rear contacts, i.e. with the existence of a potential barrier for majority charge carriers in the near-contact region.

The corresponding researches demonstrated that such photosensitive structures with non-Ohmic rear contacts are characterized by a lower efficiency of phototransformation than that of SCs with Ohmic contacts, so that it is inexpedient to use the former as SCs. On the other hand, the non-Ohmic behavior of rear contacts substantially changes the character of nonequilibrium processes, which include the generation, recombination, and collection of charge carriers in photosensitive structures, and this fact has to be taken into account when characterizing SCs. To specify the model ideas about the mechanisms of influence of non-Ohmic rear contact parameters on the formation of the open-circuit voltage and the short-circuit current, we carried out, in this work, a comprehensive analysis of the lux-volt dependences $V_{OC}(P_L)$ and the spectral characteristics of the short-circuit current $I_{SC}(\lambda)$ and the open-circuit voltage $V_{OC}(\lambda)$. We theoretically analyzed the regularities in the formation of a small-signal photovoltage, provided that there is a layer with majority charge carrier depletion under the metal electrode on the back surface, and compared the results obtained with experimental ones.

2. Experimental Technique

The researches were carried out on silicon photosensitive structures with the base of p- or n-type conductivity and the geometrical dimensions of 5×5 mm^2. Emitter regions were created with the help of the thermal diffusion of doping impurities, and the front and rear contacts were deposited by magnetron sputtering of aluminum. The contact with the back (dark) surface was continuous, and the front electrode was a collection of long narrow "fingers" that were connected together by means of a wider central bus. The front surface was covered with a two-layer antireflecting coating Si_3N_4+SiO_2. For the sake of comparison, we also studied the phototechnical characteristics of silicon SCs with the structure p^+-n-n^+ or n^+-p-p^+ and with Ohmic rear contacts.

The structures with either Ohmic or non-Ohmic rear contact were used to study the dependences of the open-circuit voltage in a wide range of irradiance under AM1.5 spectral conditions, as well as the spectral dependences of the small-signal photovoltage and the short-circuit photocurrent in the wavelength range 400–1200 nm. In the course of spectral researches, a fixed level of specimen surface irradiance was maintained automatically, and the spectral dependences of the current and the voltage were

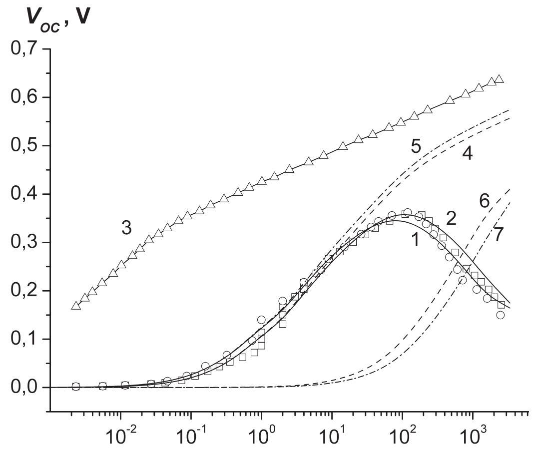

Fig. 1. Dependences of the open-circuit voltage on the specimen irradiance for silicon photosensitive structures fabricated on the basis of a substance with the p-type conductivity, and with non-Ohmic (curves *1* and *2*) and Ohmic (curve *3*) rear contacts. Points denote experimental data, curves *1* and *2* are the results of theoretical simulations. Curves *5* and *6* are the calculated photovoltages for the illuminated and rear, respectively, surfaces of specimen 1, and curves *4* and *7* are the same for specimen 2

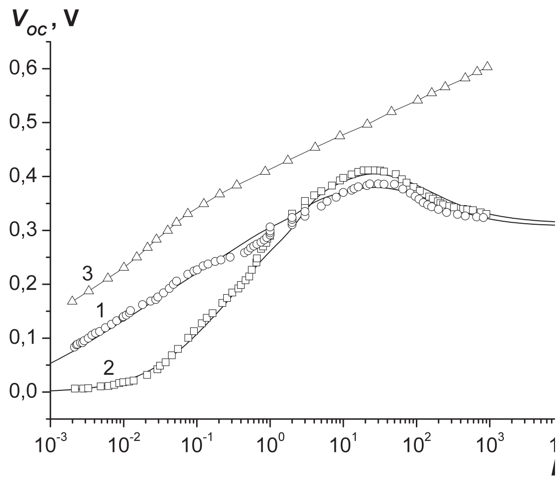

Fig. 2. Dependences of the open-circuit voltage on the specimen irradiance for silicon photosensitive structures fabricated on the basis of a substance with the n-type conductivity, and with non-Ohmic (curves *1* and *2*) and Ohmic (curve *3*) rear contacts. Points denote experimental data, curves *1* and *2* are the results of theoretical simulations

recalculated to the fixed density of light quantum flux that fell upon the structure surface. In the course of phototechnical and spectral measurements, we used an instrumentation equipment supplied by the Center for testing photoconverters and photoelectric batteries of the V.E. Lashkarev Institute of Semiconductor Physics of the National Academy of Sciences of Ukraine and certified by the State Committee of Ukraine for Technical Regulation and Consumer Policy.

3. Experimental Results

Our experimental researches showed that the dependences of the open-circuit voltage V_{OC} on the irradiance P_L are nonmonotonic (their plots have a maximum) for silicon photosensitive structures with non-Ohmic rear contact (circles and squares in Figs. 1 and 2). Such a shape is characteristic of the structures fabricated on the basis of silicon wafers with either p- (Fig. 1) or n-type (Fig. 2) of conductivity. For the sake of comparison, each figure also includes the dependence $V_{OC}(P_L)$, obtained for SC specimens with Ohmic rear contact (triangles). In the latter case, characteristic is the linear dependence of the open-circuit voltage on the logarithm of irradiance with two slopes, which agrees with known theoretical and experimental results.

According to the experimental data depicted in Figs. 1 and 2, the increase of irradiance P_L gives rise first to a monotonic growth of the open-circuit voltage in structures with non-Ohmic rear contacts up to maximal values falling within the interval 350–420 mV (at $P_L \approx 10^1 \div 10^2$ W/m^2) and, then, to its monotonic drop. Similar dependences were also observed for other structures with non-Ohmic rear contact, with the maximal V_{OC}-values being observed at the same irradiance levels as in Figs. 1 and 2, and falling within the interval from 260 to 420 mV.

The analysis of the spectral dependences of the short-circuit current I_{SC} and the open-circuit voltage V_{OC}, both normalized by the corresponding value at the maximum and the incident quantum flux density, showed that, in the case of structures with the base of n-type, those dependences practically coincide with one another at every wavelength (Fig. 3, curves *1* and *2*). Such specimens are characterized by lower short- and long-wave sensitivities in comparison with SCs with Ohmic rear contact (Fig. 3, curve *3*). On the other hand, in the case of structures with the base of p-type, the spectral dependences of the open-circuit voltage and the short-circuit current coincide only in the short-wave spectral section (Fig. 4, curves *1* to *3*). At the same time, the shape of the spectral dependence of the open-circuit voltage in the long-wave range turns out somewhat different from that of the short-circuit current, being also depen-

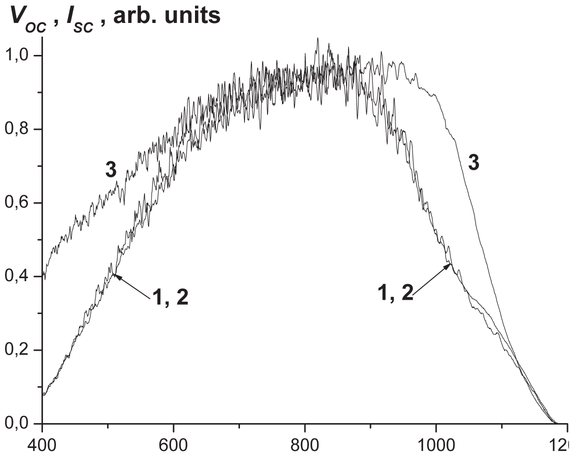

Fig. 3. Spectral dependences of the open-circuit voltage (curve *1*) and the short-circuit current (curves *2* and *3*), normalized by the corresponding maximal value and the constant flux density of incident quanta, for SC specimens with non-Ohmic (curves *1* and *2*) and Ohmic (curve *3*) rear contacts and fabricated on the basis of silicon with the n-type conductivity

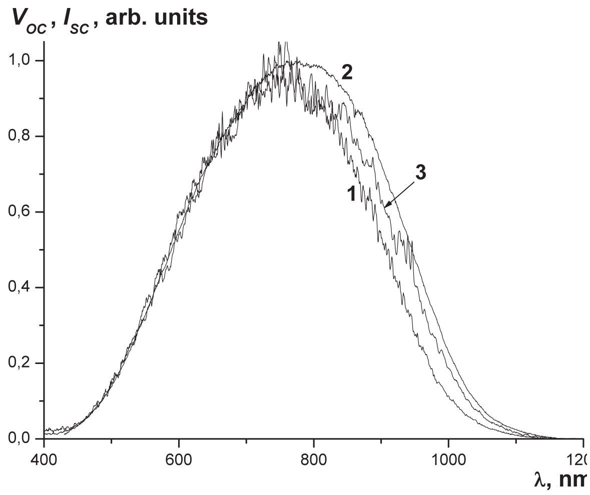

Fig. 4. Spectral dependences of the open-circuit voltage at $V_{max} \approx$ 0.3 mV (curve *1*) and $V_{\max} \approx 3.5$ mV (curve *2*) and short-circuit current (curve *3*), normalized by the corresponding maximal value and the constant flux density of incident quanta, for SCs with non-Ohmic rear contact and fabricated on the basis of silicon with the p-type conductivity

dent on the irradiance level (Fig. 4, curves *1* and *2*). In particular, the increase of P_L-value and the open-circuit voltage in the maximum from 0.3 to 3.5 mV left the short-wave sensitivity of SC practically unchanged, whereas the long-wave one grew noticeably (Fig. 4). For such structures, a characteristic feature was also lower short- and long-wave sensitivities than those in the case of structures with the base of n-type.

The essential modification of the spectral dependence of photosensitivity, which is revealed by SCs with non-Ohmic rear contact in the long-wave range (the dependence shifts toward short waves) makes impossible the correct determination of the diffusion length L of minority charge carriers on the basis of spectral dependences of the small-signal photovoltage or photocurrent, in particular, by the method described in work [3]. The L-values determined by this method would be considerably underestimated, and the corresponding error would depend in a complicated manner on the rear barrier parameters, in particular, on its height.

4. Theoretical Model of Silicon Structures with Non-Ohmic Rear Contact

Two approaches are used for the theoretical simulation of the open-circuit voltage in silicon photosensitive structures. One of them is based on the calculation of the excess concentration Δn of electron-hole pairs at the boundary between the space charge region (SCR) and the quasineutral volume of semiconductor, taking every mechanisms of recombination into account; in particular, these are the Shockley–Reed–Hall recombination in the semiconductor bulk, recombination in the near-surface SCR, and surface recombination. Such a calculation is usually carried out, by supposing that the injection level is small enough, i.e. Δn is lower than the equilibrium concentration n_0 of majority charge carriers in the base. In this case, the rate of bulk recombination $V_d = D_p/L_d$, where D_p is the diffusion coefficient of minority charge carriers and L_d their diffusion length, does not depend on the injection level, and the effective rate of recombination in the SCR $V_{SC} = V_{SC}^0\sqrt{p_0/\Delta n}$, where p_0 is the equilibrium concentration of minority charge carriers in the base, decreases with the growth of the injection level. Therefore, the contribution of the latter recombination can dominate only provided low enough injection levels. In this case, the open-circuit voltage grows with the injection level twice as quick as in the case where either the bulk or surface recombination dominates ($V_{OC} = (2kT/q)\ln(I/p_0V_{SC}^0)$, where I is the rate of optical generation of electron-hole pairs).

In the case of large injection level, i.e. when $\Delta n > n_0$, the recombination, besides the mechanisms of bulk Shockley–Reed–Hall and surface recombinations, envolves also the mechanisms of higher orders, in particular, square-law and cubic recombinations. Provided that the analytical dependences of those recombination rates on Δn are known, it is possible to calculate the dependence of V_{OC} on the injection level in this case as well (see, e.g., work [4]). An advantage of such an approach is that it allows the contributions made to the open-circuit voltage V_{OC} by the illuminated and back surfaces, as well as their spectral dependences, to be calculated separately, by solving the diffusion equation for excess electron-hole pairs with corresponding boundary conditions. However, under certain conditions—in particular, at low temperatures and at small injection levels—the recombination currents can possess the tunnel origin. Their dominant role results, as a rule, in that the non-ideality factor of light current-voltage characteristics (CVCs) of a photosensitive structure becomes more than two. In most cases, the value of V_{OC} can be calculated theoretically, if one assumes that the light CVC can be described by two current components, one of which is characterized by the non-ideality factor close to 1 and the other by the non-ideality factor A. Then the open-circuit voltage at large enough values of shunting resistance can be determined from the equation

$$J_{1s}\left(\exp\left(\frac{qV_{OC}}{kT}\right)-1\right)+$$

$$+J_{2s}\left(\exp\left(\frac{qV_{OC}}{AkT}\right)-1\right)=J_{SC}, \quad (1)$$

where J_{1s} and J_{2s} are the densities of saturation current components, and J_{SC} is the short-circuit current density. The case $A = 2$ where the contribution of the second component in Eq. (1) prevails is actually reduced to the case considered above, where the rate of recombination in the SCR dominates.

An advantage of the second approach is that, by introducing the non-ideality factor A, one can simulate the open-circuit voltage even in the case where the recombination current has a tunnel character. Its shortcoming is the impossibility to obtain spectral dependences for V_{OC}. Note that, in the framework of the second approach, the results of the first one can be generalized to the case where the recombination current is governed by the tunnel mechanism. The matter is that tunnel currents run only in the SCR. Therefore, it is possible to introduce the generalized effective rates of surface recombination, which would take both the conventional mechanism of surface recombination and the tunnel one in consideration. In the case of an arbitrary injection level, for the illuminated and rear surfaces of a photosensitive structure, the following formulas can be written down:

$$S_0^*=S_0+\frac{J_{1s}^0}{q}\left(\left(\frac{\Delta n_0}{p_0}+1\right)^{1/A_0}-1\right)\Delta n_0^{-1}, \quad (2)$$

$$S_d^*=S_d+\frac{J_{1s}^d}{q}\left(\left(\frac{\Delta n_d}{p_0}+1\right)^{1/A_d}-1\right)\Delta n_d^{-1}. \quad (3)$$

Here, the indices 0 and d relate the corresponding quantities – the effective surface recombination rate S, the saturation current J_{1s}, the excess concentration of electron-hole pairs Δn, and the non-ideality factor A – to the illuminated or back surface, respectively.

It is easy to verify that, if the second components in Eqs. (2) and (3) dominate in the recombination current, the expression for the open-circuit voltage looks like $V_{OC} = kT/q(\ln(\Delta n/p_0) + 1)$ and coincides with the expression $V_{OC} = AkT/q(\ln(J_{SC}/J_{1s})+1)$. On the other hand, at larger $A_{0(d)}$, the role of second components in Eqs. (2) and (3) diminishes with increase in the injection level.

5. Results of Theoretical Simulation and Their Discussion

The approach considered above allows, in principle, the spectral and lux-ampere dependences for the excess concentration of electron-hole pairs in silicon photosensitive structures to be obtained and the open-circuit voltage to be calculated, taking tunnel currents into account. However, the corresponding number of parameters is too large for the solution of the inverse problem to be unambiguous. Therefore, in order to compare theoretical lux-volt dependences with experimental ones, let us use the following system of equations:

$$V_{OC}=V_{OC}^0-V_{OC}^d, \quad (4)$$

$$J_{1s}^0\left(\exp\left(\frac{qV_{OC}^0}{kT}\right)-1\right)+$$

$$+J_{2s}^0\left(\exp\left(\frac{qV_{OC}^0}{A_0kT}\right)-1\right)=J_{SC}, \quad (5)$$

$$J_{1s}^d\left(\exp\left(\frac{qV_{OC}^d}{kT}\right)-1\right)+$$

$$+J_{2s}^d\left(\exp\left(\frac{qV_{OC}^d}{A_dkT}\right)-1\right)=mJ_{SC}, \quad (6)$$

where $m \ll 1$.

It is worth noting that expressions (4)–(6) can be used for the calculation of V_{OC}, provided that the quantities J^d_{1s}, J^d_{2s}, and m satisfy the conditions $J^d_{1s}/m = B_1$ and $J^d_{2s}/m = B_2$, where B_1 and B_2 are some constants. Therefore, the quantity m, the physical meaning of which is the ratio between the excess concentrations of electron-hole pairs near the rear, Δn_d, and illuminated, Δn_0, surfaces, has to be determined independently. This can be done, if the structure thickness, recombination parameters, and spectral composition of light are known. For calculations, we used $m = 4.7 \times 10^{-4}$ for specimens with n-base, and $m = 2.3 \times 10^{-4}$ for specimens with p-base. Below, we discuss the procedure of their determination in more details.

The values of theoretical model parameters, at which an agreement between the experimental dependences $V_{OC}(P_L)$ and theoretical ones (curves *1* and 2 in Figs. 1 and 2) was attained, are listed in Table 1. These are the saturation currents J^0_{1s}, J^0_{2s} and J^d_{1s}, J^d_{2s} for the illuminated and rear surfaces of the first and second specimens, and the corresponding non-ideality factors. In Fig. 1, we also plotted—for the same parameter values—the theoretical dependences of the photovoltage that arises on the illuminated and rear surfaces of the first and second specimens on P_L (curves *4* to *7*). As is seen from Fig. 1, the photovoltage on the rear surface (curves *6* and *7*) appears in the vicinity of $V_{OC}(P_L)$-maximum and grows with P_L faster than the photovoltage on the illuminated surface (curves *4* and *5*), just this fact being responsible for the emergence of maximum.

Figures 1 and 2 also demonstrate that the experimental and theoretical dependences $V_{OC}(P_L)$ are in good agreement with each other in a wide range of irradiance variation.

Now, let us consider the calculation procedure for the spectral dependences of the small-signal open-circuit voltage in structures with n-base and non-Ohmic rear contact. In Fig. 5, the energy diagrams of such structures are depicted schematically, and the planes, at which the surface recombination and the recombination in the SCR are taken into account, are indicated. The calculations are executed provided some simplifications. In particular, we consider first that the influence of the

J^0_{s1}, A/cm^2	J^0_{s2}, A/cm^2	J^d_{s1}, A/cm^2	J^d_{s2}, A/cm^2	A^0	A^d
$4{\cdot}10^{-11}$	10^{-5}	10^{-12}	$8.7{\cdot}10^{-7}$	3	4.6
10^{-11}	$7{\cdot}10^{-6}$	10^{-12}	$5.6{\cdot}10^{-7}$	2.9	4.7
10^{-11}	10^{-8}	$8{\cdot}10^{-10}$	$3.6{\cdot}10^{-7}$	1.5	2.7
10^{-11}	10^{-8}	$8{\cdot}10^{-10}$	$3.6{\cdot}10^{-7}$	3	3

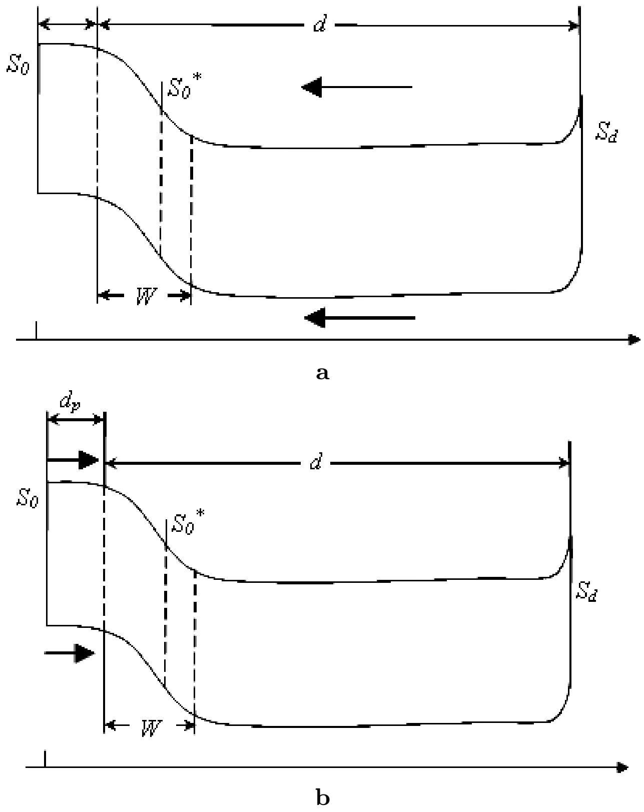

Fig. 5. Schematic energy diagrams for a photosensitive structure with n-base and planes, in which the surface recombination and recombination in the SCR occur, in the cases where the bulk (a) ($\alpha(d_p + w) \ll 1$) or surface (b) ($\alpha d_p \gg 1$) optic generation dominates

front surface and the heavily doped n^+- or p^+-region near the illuminated contact at the excess concentration of electron-hole pairs can be described by introducing the effective rate of surface recombination S^*_0. Generally speaking, it is correct, if two conditions are satisfied: (i) the Fermi quasilevel for minority charge carriers in the near-surface SCR is constant, and (ii) the generation of electron-hole pairs occurs beyond the heavily doped near-surface region, i.e. the criterion $\alpha d_p < 1$, where α is the coefficient of light absorption, and d_p is the thickness of a heavily doped layer (Fig. 5,a), is fulfilled.

Let us obtain, under the indicated simplifications, the theoretical spectral dependences for the excess concentration of electron-hole pairs at the internal SCR boundaries localized near the illuminated, Δn_0, and rear, Δn_d, surfaces in the case of their monochromatic illumination and provided that the open-circuit mode is realized. For this purpose, let us use the solution of the standard diffusion equation and determine the integration constants from the boundary conditions for fluxes across the illuminated and rear surfaces. Then, we obtain

$$\Delta n_0 = \frac{\alpha L I(1-R_{0)}}{1-(\alpha L)^2}\left\{\left[(S_d+V_d)e^{d/L}\times\right.\right.$$

$$\times\left[\frac{S_0^*}{V_d}\left(1+R_d e^{-2\alpha d}\right)+\alpha L\left(1-R_d e^{-2\alpha d}\right)\right]-$$

$$-(S_0^*-V_d)\left[\frac{S_d}{V_d}(1+R_d)-\alpha L(1-R_d)\right]\times$$

$$\times e^{-\alpha d}+(V_d+S_0^*)\left[\frac{S_d}{V_d}(1+R_d)-\alpha L(1-R_d)\right]\times$$

$$\times e^{-\alpha d}-(S_d-V_d)e^{-d/L}\left[\frac{S_0^*}{V_d}(1+R_d)+\right.$$

$$\left.\left.+\alpha L(1-R_d)\right]e^{-2\alpha d}\right]\left[(S_0^*-V_d)\,(S_d-V_d)\,e^{-d/L}-\right.$$

$$\left.-\,(S_0^*+V_d)\,(S_d+V_d)\,e^{d/L}\right]^{-1}+$$

$$\left.+\frac{1+R_d e^{-2\alpha d}+\alpha L(1-R_d)e^{-d/L-\alpha d}}{V_d}\right\}, \qquad (7)$$

$$\Delta n_d = \frac{\alpha L I(1-R_{0)}}{1-(\alpha L)^2}\left\{\left[\left[(S_d+V_d)e^{d/L}\times\right.\right.\right.$$

$$\times\left[\frac{S_0^*}{V_d}\left(1+R_d e^{-2\alpha d}\right)+\alpha L\left(1-R_d e^{-2\alpha d}\right)\right]-$$

$$\left.\left.-(S_0^*-V_d)\left[\frac{S_d}{V_d}(1+R_d)-\alpha L(1-R_d)e^{-\alpha d}\right]\right]\right]\times$$

$$\times e^{-d/L}+\left[(V_d+S_0^*)\left[\frac{S_d}{V_d}(1+R_d)-\alpha L(1-R_d)\right]\times\right.$$

$$\times e^{-\alpha d}-(S_d-V_d)e^{-d/L}\left[\frac{S_0^*}{V_d}(1+R_d)+\right.$$

$$\left.\left.+\alpha L(1-R_d)\right]e^{-2\alpha d}\right]e^{d/L}\Big]\left[(S_0^*-V_d)\,(S_d-V_d)\,\times\right.$$

$$\left.\times e^{-d/L}-(S_0^*+V_d)\,(S_d+V_d)\,e^{d/L}\right]^{-1}+$$

$$\left.+\frac{(1+R_d+\alpha L(1-R_d))e^{-\alpha d}}{V_d}\right\}, \qquad (8)$$

where L is the diffusion length for electron-hole pairs, d the base thickness, V_d the diffusion rate, I the rate of optic generation, S_0^* and S_d are the effective rates of surface recombination at the illuminated and rear surfaces, respectively, and R_0 and R_d are the coefficients of light reflection from the illuminated and rear surfaces, respectively.

The spectral dependences of the quantities Δn_0 and Δn_d are driven by values of the products αd and αL. Under the condition $\alpha d > 1$, the illumination is absorbed practically completely in the semiconductor, whereas, if $\alpha L > 1$, the case of strong light absorption is realized, at which the diffusion supplies nonequilibrium carriers to the illuminated and rear surfaces. The case $d \geq L$ is of interest for the analysis. If the strong inequality $d \gg L$ is satisfied, then, provided $\alpha d > 1$, the limiting case where $\Delta n_0 = \alpha L I/(1+\alpha L)S_0^*$ and $\Delta n_d \approx 0$ is realized. In this case, the dependence $V_{OC}(P_L)$ is monotonous and practically not affected by the sign and the magnitude of band bending at the rear surface. The corresponding diffusion length L can be found from the spectral dependences of the short-circuit current or small-signal photovoltage in the framework of the standard method described in work [3].

The total amplitude of the small-signal open-circuit voltage in a structure with non-Ohmic rear contact can be determined in the case of monochromatic illumination from the expression

$$V_{OC} = kT/q\,(\Delta y_0 - \Delta y_d)\,, \qquad (9)$$

where Δy_0 and Δy_d are the dimensionless variations of the surface band bending at the front and rear, respectively, surfaces subjected to illumination.

In the case of inverse band bending at the illuminated surface, the dimensionless open-circuit voltage is determined by the relation

$$\Delta y_0 = -\frac{\Delta n_0}{n_0}. \qquad (10)$$

At the same time, in order to determine the magnitude and the spectral dependence of Δy_d, provided that there are depleted or inversion layers near the rear surface, one has to use the equation of integral neutrality, where not only the charge redistribution in the SCR at the illumination but also the recharge of surface states at the semiconductor-insulator interface should be considered. If the surface state recharge is neglected, the following equation becomes true:

$$\Delta y_d = -\frac{\Delta n_d(\exp(y_{0d}) - 1)}{n_0 \exp(y_{0d}) + p_0}, \quad (11)$$

where p_0 and n_0 are the equilibrium concentration of holes and electrons, respectively, in the base; and y_{0d} is the dimensionless equilibrium band bending at the rear surface before illumination.

Under AM0 conditions, when the Sun's radiation spectrum is approximated by that of a black-body at a temperature of 5800 K, the magnitude of small-signal open-circuit voltage V_{OC} for silicon structures with non-Ohmic rear contact in the absence of the surface state recharge under illumination can be determined from the expression

$$V_{OC} = kT/q \frac{3.024 \times 10^{18}}{In_0} \times$$

$$\times \int_0^1 \frac{\left[\Delta n_0(z) - \Delta n_d(z) \frac{(\exp(y_{0d})-1)}{n_0 \exp(y_{0d})+p_0}\right] dz}{z^4 \left(e^{\frac{2.261}{z}} - 1\right)}, \quad (12)$$

where $z = \lambda/\lambda_x$, λ is the light wavelength, $\lambda_x \approx 1.13\ \mu$m is the red threshold of the photoeffect in silicon at room temperature, and the quantities Δn_0 and Δn_d are substituted into Eq. (12) from expressions (7) and (8).

The approach described above allows one to obtain the spectral dependences for the small-signal open-circuit voltage in structures with non-Ohmic contact in the long-wave range, where the criterion $\alpha d_p < 1$ is satisfied. The main point here is to take the contribution of the rear surface to V_{OC} into account, which has an opposite sign in comparison with a contribution of the illuminated surface, which brings about a faster decrease of the open-circuit voltage in the long-wave range. Under those conditions, the application of the spectral dependence of V_{OC} in the long-wave range for the determination of the diffusion length gives very small values which are not valid.

It should be noted that a simple calculation that does not take the surface state recharge, i.e. the effect of surface sticking of minority charge carriers [5, 6], into account leads to only a qualitative agreement between the theory and the experiment. To achieve the quantitative agreement, it is necessary that the indicated effect be taken into consideration. When calculating the small-signal open-circuit voltage, this can be made in a rather simple way, by introducing the dimensionless parameter of surface sticking, the value of which is more than one [5]. The application of other parameters (the doping level, the diffusion length, the effective rate of surface recombination, and the SC base thickness) determined independently allows one to put the calculated spectral dependences of the small-signal open-circuit voltage in agreement with experimental ones in the long-wave range and to find the coefficient m which makes allowance for the concentration gradient of nonequilibrium minority charge carriers in the base region of the structure. Just in this way, the values $m \approx 4.7 \times 10^{-4}$ for specimens with n-base and $m \approx 2.3 \times 10^{-4}$ for specimens with p-base were determined. They were used when putting the experimental and theoretical dependences $V_{OC}(P_L)$ in agreement.

As was said above, to calculate the spectral dependences of V_{OC} V _ {OC} in the simplified approach, the approximation of a constant Fermi quasilevel for minority charge carriers was used. However, in the general case, this approximation can be not fulfilled. Table 1 demonstrates that the CVC non-ideality factors reach values more than or equal to 3, and the saturation current densities do the values from 10^{-6} to 10^{-5} A/cm^2. The recalculation of those data to the effective surface recombination rates (SRRs) near the illuminated surface, which takes expression (2) into account, shows that S_0^* reaches 10^7 cm/s at small injection levels. Provided such large values, the SRR magnitude is confined by the delivery velocity of generated minority charge carriers to the recombination site. Then, in a simple enough approximation, similarly to what was made in work [5], we can write

$$S_0^* = \left(S_0^{**-1} + \left(\frac{D_p}{e^{-\alpha d_p} \int\limits_0^w e^{-ax+y(x)} dx} \right)^{-1} \right)^{-1}, \quad (13)$$

where S_0^{**} is the maximum possible value of effective recombination rate in the near-surface SCR, w the SCR thickness, and $y(x)$ the dimensionless potential in the SCR of a $p-n$-transition. Expression (13) can be used only in the case where the electron-hole pairs are generated to the right from the recombination plane (see Fig. 5,a). This means that the criteria $\alpha d_p < 1$ and $\alpha(d_p + w) > 1$ should be valid. Typical values of d_p and w in the structures under consideration amount to about 1 μm each; therefore, it is difficult enough to satisfy both criteria simultaneously. But if the criterion $\alpha d_p \gg 1$ holds true (see Fig. 5,b), i.e. practically all electron-hole pairs are generated to the left from the recombination plane, the situation is changed, and the spectral dependence of the small-signal open-circuit voltage practically coincides with that of the short-circuit current at large S_0^{**}-values. This can be easily verified by considering the boundary conditions for the calculation of spectral dependences of the short-circuit current and the small-signal V_{OC}. In particular, in the case of short-circuit current, we have

$$j(x=0) = -S_0 \Delta n(x=0), \tag{14}$$

$$\Delta n(x=d_p) = 0. \tag{15}$$

When calculating the small-signal V_{OC}, boundary condition (14) is also used, whereas the second condition is an equation which can be written in the form

$$\Delta n(x=d_p) = \frac{j(x=d_p)}{S_0^{**}}. \tag{16}$$

Here, $j(x)$ is the flux of nonequilibrium electrons in the heavily doped p^+-region, and $\Delta n(x)$ is their excess concentration.

Provided that the criterion $S_0 \ll S_0^{**}$ holds true, the flux of electrons directed from the front surface to the $p-n$-transition dominates. Since the value of S_0^{**} can reach 10^7 cm/s, and the S_0-values do not exceed usually 10^5 cm/s, the use of expressions (15) and (16) gives practically the same result. In practice, this means that the spectral dependences of the small-signal open-circuit voltage and the short-circuit current in the short-wave absorption range may coincide. In Figs. 3 and 4, one can see that the spectral dependences of V_{OC} and the short-circuit current in structures with the base of either p- or n-type really coincide in the short-wave range, which confirms the validity of the criterion given above. On the other hand, a shift of the spectral dependences of the open-circuit voltage toward long waves, which accompanies the increase of the surface irradiance (curve *2* in Fig. 4), can be caused, in accordance with Eq. (3), by a reduction of the effective recombination rate S_0^d under nonlinear conditions.

6. Conclusions

The non-Ohmic character of a rear contact in silicon photosensitive structures has been found to be responsible for the nonmonotonic character of the dependences of the open-circuit voltage V_{OC} on the surface irradiance P_L and its more drastic drop in the long-wave spectral range in comparison with the Ohmic-contact case. A two-exponential model of silicon structure with non-Ohmic rear contact has been proposed, and the corresponding model parameters for the specimens studied in this work have been determined. It has been shown that the two-exponential model provides a quantitative agreement between the theoretical and experimental dependences $V_{OC}(P_L)$ in a wide range of irradiance of silicon structure surfaces.

The theoretical and experimental spectral dependences of the open-circuit voltage and the short-circuit current in silicon structures with non-Ohmic rear contact, normalized by their corresponding maximal values, have been compared, which enabled us to find criteria for the coincidence of those dependences in the short-wave spectral range. At the same time, the dependences do not coincide in the long-wave range, where their shapes turn out dependent on the surface irradiance level.

It has been shown that, owing to the substantial variation of the spectral dependence of the photosensitivity of structures with non-Ohmic rear contact in the long-wave range, the correct determination of the diffusion length of minority charge carriers L on the basis of a spectral dependence of the small-signal photovoltage (or photocurrent) is impossible in the framework of the standard method. The corresponding L-values turn out substantially underestimated, and their error depends on the rear barrier parameters in a complicated manner.

It has been demonstrated that the measurements of the lux-ampere and lux-volt dependences allows an important additional information to be obtained concerning the properties of rear contacts in photosensitive structures and their influence on the efficiency of photoelectric energy transformation processes in SCs.

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ФОТОЕЛЕКТРИЧНІ ХАРАКТЕРИСТИКИ КРЕМНІЄВИХ ФОТОЧУТЛИВИХ СТРУКТУР З НЕОМІЧНИМИ ТИЛОВИМИ КОНТАКТАМИ

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Р е з ю м е

Проведено детальні дослідження залежностей напруги розімкненого кола від рівня енергетичної освітленості $V_{OC}(P_L)$, спектральних залежностей струму короткого замикання $I_{SC}(\lambda)$ і напруги розімкненого кола $\mathrm{V}_{OC}(\lambda)$ зразків кремнієвих фоточутливих структур з немонотонною (з максимумом) залежністю $V_{OC}(P_L)$. Встановлено, що особливості залежностей від рівня енергетичної освітленості зумовлені неомічністю тилового контакту досліджених структур. Запропоновано модельні уявлення про механізми впливу характеристик тилового контакту на процеси генерації, рекомбінації і збирання носіїв заряду в фоточутливих структурах. Показано, що в межах запропонованої моделі має місце кількісне узгодження теоретичних і експериментальних залежностей $V_{OC}(P_L)$ в широкому діапазоні зміни енергетичної освітленості поверхні кремнієвих фоточутливих структур. Показано, що вимірювання залежностей $V_{OC}(P_L)$ і $I_{SC}(P_L)$ необхідно використовувати як додатковий метод характеризації фоточутливих структур, який дозволяє отримати важливу додаткову інформацію про властивості їхніх тилових контактів.