THICKNESS DEPENDENCES OF PHOTOELECTRIC CHARACTERISTICS OF SILICON BACKSIDE CONTACT SOLAR CELLS

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The thickness dependences of the photocurrent quantum yield and photoenergy parameters of silicon backside contact solar cells (BC SC) are investigated theoretically and experimentally. The surface recombination rate on the irradiated surface was minimized by means of creating the layers of microporous silicon. A method of finding the surface recombination rate and the diffusion length of minority carriers from the thickness dependences of the photocurrent quantum yield under conditions of the strong absorption is proposed. The performed studies allowed us to establish that the thinning of the BC SC samples in the case of minimizing the surface recombination rate gives a possibility to achieve rather high efficiencies of photoconversion. It is also shown that the agreement between the experimental and theoretical spectral dependences of the photocurrent quantum yield can be reached only with regard for the coefficient of light reflection from the backside surface.

1. Introduction

Silicon backside contact (BC) solar cells (SC) with n-type base, as well as solar batteries produced on their basis, have the highest efficiency of photoelectrical energy conversion η achieved for today that reaches 20 % for serial modules [1]. The thickness of the quasineutral base region in such BC SCs is usually much smaller than the diffusion length of minority carriers, whereas the effective surface recombination rate S^* on the front (nonmetallized) surface referred to the inner boundary of the near-surface space charge region (SCR) is minimized to the level having practically no influence on the value of η.

As is known, the most effective way of eliminating the surface recombination losses in BC SCs is to generate isotype $n^+ - n$ or $p^+ - p$ junctions on their front surface that limit the supply of nonequilibrium minority carriers to surface recombination centers [2,3]. In the presence of such junctions, the effective surface recombination rate S^* is minimized due to a decrease of the minority carrier fluxes via surface recombination centers [2]. Though, at high doping levels of the surface layer, the rate S^* can increase due to an increase of the Auger recombination rate in it [3].

A number of works [4, 5] used another way of minimizing the negative influence of surface recombination losses on the BC SC efficiency η, namely the formation of floating $p^+ - n$ or $n^+ - p$ junctions on their front surface that limited the supply of nonequilibrium majority carriers to surface recombination centers. However, the experimental researches [5] demonstrated that, though the formation of a floating $n^+ - p$ junction really resulted in an increase of the BC SC efficiency η under the standard spectral AM1.5 conditions at the irradiance $P = 1000$ W/m^2, a considerable (tens-fold) rise of the effective surface recombination rate S^* was simultaneously observed. As was shown in our work [6], the increase of S^* is related to the contribution of the SCR recombination that can be very significant in the case of low-intensity irradiance.

If the initial thickness of a BC SC exceeds the diffusion length of minority carriers, then its thinning must result in a considerable rise of the short-circuit current and the photoconversion efficiency. This work is devoted to experimental and theoretical studies of the thickness dependences of the quantum yield and photoenergy parameters of BC SCs. The effective surface recombination rate after a regular thinning of a BC SC sample was minimized by means of creating a microporous silicon layer on the sample surface. We propose a method of determination of the effective surface recombination rate S^* and the diffusion length of minority carriers L from the thickness dependences of the BC SC quantum yield under conditions of the strong light absorption in a semiconductor. It is established that the long-wavelength maximum at the spectral dependences of the BC SC short-circuit current perceptibly depends on the coefficient of light reflection from the BC SC backside metallized surface.

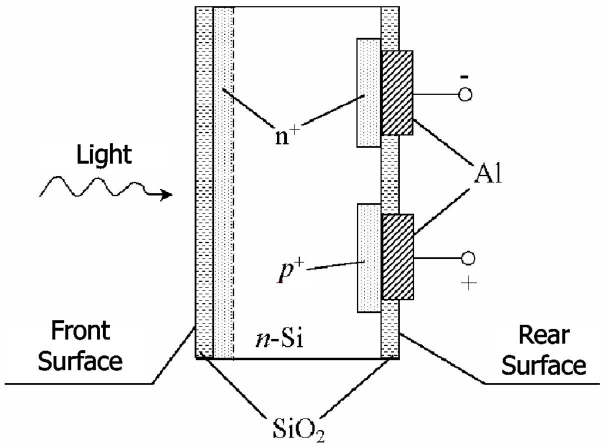

Fig. 1. Diagram of a silicon backside contact solar cell

2. Experimental Technique

The recombination activity was studied using experimental samples of silicon BC SCs from two groups with initial thicknesses of 400 μm. Their schematic cross section is shown in Fig. 1. The samples were produced on plates of n-type zone-melting silicon with the resistivity $\rho = 2$ Ohm·cm. A near-surface isotype $n^+ - n$ junction or a floating $p^+ - n$ junction was formed on the front (irradiated) surface 2 cm^2 in area. The front surface of the BC SCs was additionally passivated by a thermal SiO_2 layer with a thickness approximating 110 nm, which reduced the optical losses of incident light and the concentration of surface recombination-active centers on this surface. The BC SC samples without near-surface junctions with the only thermal SiO_2 layer on the front surface were also investigated.

The choice of BC SCs as an instrument for studying the nature of surface and volume recombination processes is caused by the fact that they allow one to rather easily realize the conditions, under which the region of optical generation of nonequilibrium electron-hole pairs will be localized close to the front surface and spatially separated from the collector junction by the quasineutral base region. The short-circuit current of the collector junction on the backside surface is a function of the effective surface recombination rate S^* on the front surface that depends, in turn, on the rates of recombination via surface recombination-active centers, Auger recombination in the heavily doped n^+- or p^+-layers, and recombination in the near-surface SCR. Investigating the kinetics of variation of the short-circuit current of the collector junction in the process of the BC SC thinning, it is possible to separate the contributions made to the photocurrent by the surface and volume recombinations.

The experimental BC SC samples with Al buses welded to the contact areas were firstly thermally fixed on the surface of a glass substrate with the help of an optically transparent butyral resin film. After that, the Al buses were welded with transfer metal electrodes subsequently soldered with conducting metal wires. All the components of the set-up were protected from the action of aggressive chemical substances of an electrolyte or etchant by chemical-resistant optically transparent polymer materials, so that the electrolyte or etchant could contact only with the front thermally oxidized BC SC surface.

The chemical etching was performed in a mixture of HNO_3 and HF relating as 3:1. At the chemical etching, a silicon dioxide layer close to the BC SC front surface was etched first of all, then followed the isotype $n^+ - n$ or the floating $p^+ - n$ junction, and only after that took place the etching of the base region. The thickness of the etched layers was determined by the etching time and controlled by a micrometer.

The processes of anode etching of the BC SC front surface were performed in a transparent electrochemical cell with a Pt electrode. The cell construction allowed one to irradiate the BC SC front surface by light coming from a mirror incandescent lamp through a selective optical filter SZS-26 that transmitted only photons with $\lambda < 0.75$ μm and thus provided a small (several micrometers) effective depth of optical generation of electron-hole pairs close to the BC SC front surface. The irradiance of the BC SC surface in the cell in the presence of an electrolyte approximated 700 W/m^2.

The electrochemical anodic process was performed in the galvanostatic mode at a constant current density on the sample surface (J = 2–4 mA/cm^2) and the voltage at the output of a power supply V = 2 V. The used electrolyte was a mixture of ethanol and concentrated (49%) HF taken in the ratio of 1:4. Besides the stabilized current density and the voltage across the electrolyte cell, we also controlled the short-circuit current of the backside collector junction caused by the irradiation of the BC SC front surface. The latter allowed us to determine the dynamics of the variation of recombination parameters of the BC SC front surface directly in the course of the electrochemical reaction.

Each thinning of the BC SC sample was followed by the anodization leading to the formation of a microporous silicon layer on the surface. This resulted in both the passivation of the surface and a decrease of the surface recombination rate. After etching the silicon dioxide and the heavily doped layers, the effective surface recombination rate S^* grew due to the formation of depleting band bendings on the front surface, whereas the anodization of the etched surface led to a decrease of S^* due to the hydrogen passivation of the surface.

The phototechnical and optical parameters of the BC SCs were measured with the help of a control-measuring equipment of the Center for testing photoconverters and photoelectric batteries of V.E. Lashkaryov Institute of Semiconductor Physics of the NAS of Ukraine certified by the State Committee of Ukraine for Technical Regulation and Consumer Policy. The measuring technique was as follows. First, we determined the initial phototechnical parameters of the BC SCs with a thermally oxidized surface under the AM1.5 spectral conditions and measured the spectral dependences of the short-circuit current in the wavelength range $\Delta\lambda = 0.4...1.2$ μm. Then, after each thinning and the following anodization, the BC SC sample was dried at room temperature, and the same parameters were measured once again.

3. Thickness Dependences of the Internal Quantum Yield of BC SCs

The internal quantum yield Q in silicon BC SCs in the case of monochromatic irradiation can be found from the solution of a diffusion equation with the following boundary conditions:

$$J(x=0) = -S^*\Delta p(x=0), \tag{1}$$

$$\Delta p(x=d) = 0, \tag{2}$$

where $j(x)$ and $\Delta p(x)$ are the flux of electron-hole pairs and their excess concentration in the plane x, respectively, S^* is the total rate of surface recombination S and recombination in the SCR V_{SC} in the plane $x = w$, where w is the SCR thickness.

Using the solution of the standard diffusion equation for excess electron-hole pairs with regard for the light reflection from the backside surface, we obtain the following expression for the internal quantum yield Q:

$$Q = \frac{\alpha L}{1-\alpha^2 L^2}\times$$

$$\times\Big\{-\Big[\frac{S^*L}{D}\Big((1+R_d e^{-2\alpha d}) - (1+R_d)e^{-\alpha d - d/L}\Big)+$$

$$+\alpha L(1-R_d e^{-2\alpha d}) + (1+R_d)e^{-\alpha d-d/L}\Big]\times$$

$$\times\left[\cosh(\frac{d}{L}) + \frac{S^*L}{D}\sinh(\frac{d}{L})\right]^{-1}+$$

$$+\left[(1+R_d)+\alpha L(1-R_d)\right]e^{-\alpha d}\Big\}, \tag{3}$$

where $L = \sqrt{D\tau}$ stands for the diffusion length of minority carriers, D is the diffusion coefficient, α is the light absorption coefficient, and R_d is the coefficient of light reflection from the backside surface.

The authors of [7] also obtained an expression for the spectral dependence of the BC SC internal quantum yield with the use of boundary conditions (1) and (2) and proposed a method of deriving the surface recombination rate S^* and the diffusion length of minority carriers L based on these spectral dependences. However, that study was performed without regard for the effect of light reflection from the backside surface.

In the case of strong light absorption ($\alpha L \gg 1$ and $\alpha d \gg 1$), the expression for the internal quantum yield of BC SCs significantly simplifies and takes the form

$$Q = \left(\cos h\left(\frac{d}{L}\right) + \frac{S^*L}{D}\sin h\left(\frac{d}{L}\right)\right)^{-1}. \tag{4}$$

As one can see from (4), the internal quantum yield in the case of strong light absorption does not depend on the coefficients of light absorption α and light reflection from the backside surface R_d.

In the case where the inequality $d \ll L$ is satisfied, Eq.(4) yields

$$Q = \left(1 + \frac{S^*d}{D}\right)^{-1}. \tag{5}$$

Thus, the inverse quantum yield is equal to

$$\frac{1}{Q} = 1 + \frac{S^*d}{D}, \tag{6}$$

i.e., it represents a straight-line dependence on d, whose slope S^*/D allows one to determine the surface recombination rate. However, the diffusion length cannot be found in this case.

The corresponding dependences are presented in Fig. 2,*a*.

If $d \gg L$, expression (4) yields

$$Q = \exp\left(-\frac{d}{L}\right) / \left(1 + \frac{S^*L}{D}\right). \tag{7}$$

In this case, the thickness dependences of $\ln(Q)$ are linear (Fig. 2,*b*). Moreover, the thickness dependences of Q enable one to determine the diffusion length L, whereas the accuracy of deriving the surface recombination rate S^* abruptly decreases, and it can be found

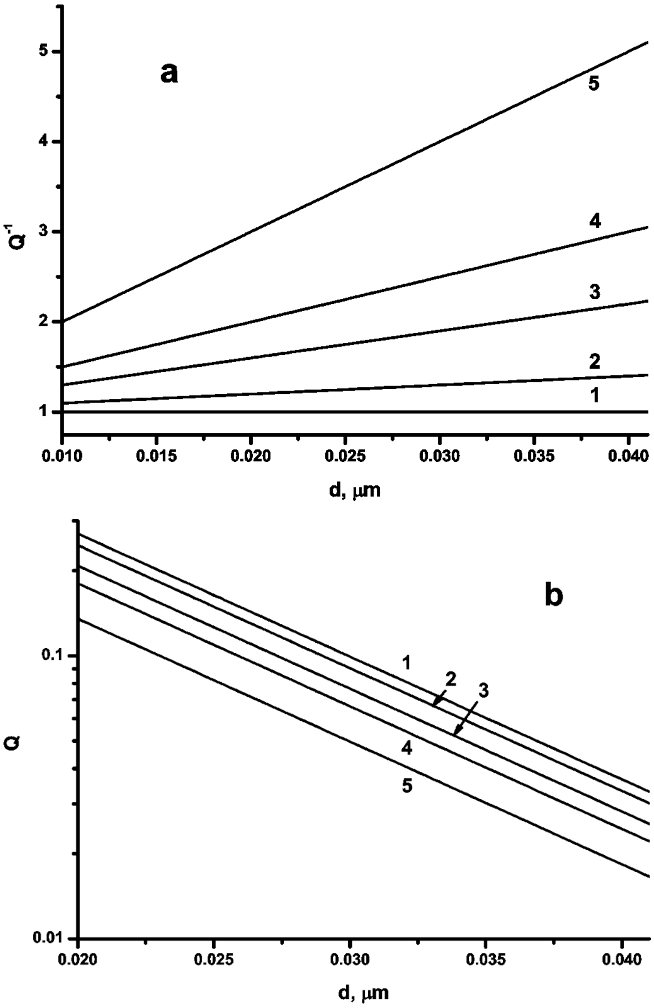

Fig. 2. Theoretical dependences of the inverse quantum yield (*a*) and quantum yield (*b*) on the thickness in the case of strong light absorption for the limiting cases of thick and thin BS SCs as compared to the diffusion length at $L = 100$ μm (*1* (*b*)) and $S^* = 1$ cm/s (*1*), 10^2 cm/s (*2*), 3×10^2 cm/s (*3*), 5×10^2 (*4*), and 10^3 (*5*)

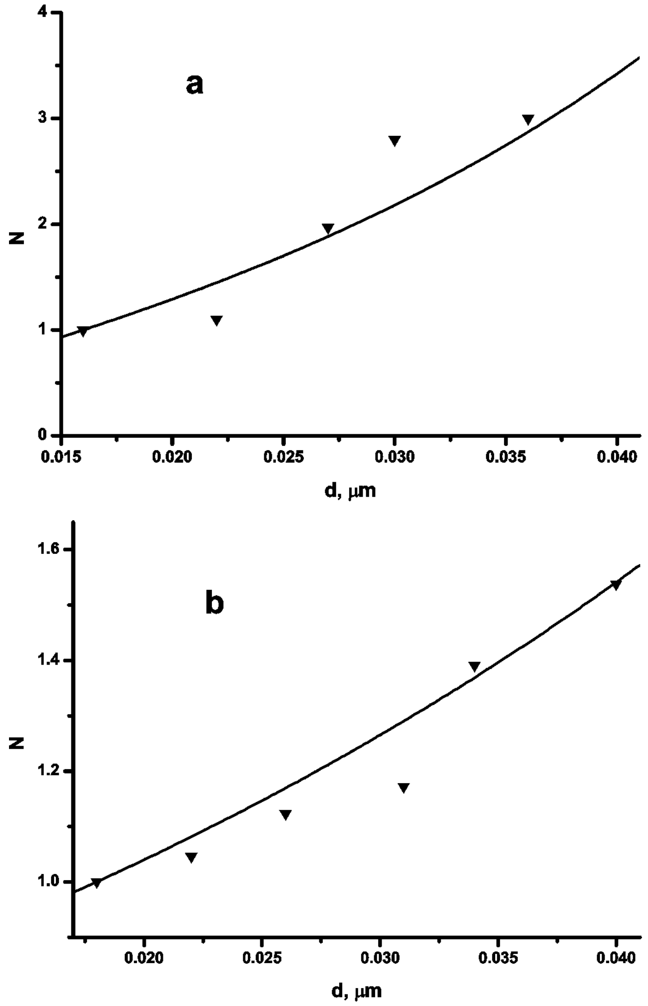

Fig. 3. Experimental (dots) and theoretical (solid lines) thickness dependences of the normalized quantum yield for the samples from the first (*a*) and second (*b*) groups. L=250 μm, $S^*= 2 \times 10^4$ cm/s (*a*); $L = 500$ μm, $S^*= 190$ cm/s (*b*)

only at $S^*L/D \geq 1$. The simultaneous determination of L and S^* from the thickness dependences of the BC SC internal quantum yield is possible only if $L \sim d$ and $S^*L/D \geq 1$.

According to (4), if the short-circuit current is measured under strong light absorption, then the ratio of the short-circuit currents at the minimum thickness $d_{\min}$ and the arbitrary thickness d is determined by the expression

$$N(d) = \frac{\cos h(d/L) + S^*L/D \sin h(d/L)}{\cos h(d_{\min}/L) + S^*L/D \sin h(d_{\min}/L)}. \qquad (8)$$

The ratio N represents an increasing function of the thickness if it changes from the minimum to the maximum value. At the known thickness d and diffusion coefficient D, dependence (8) contains two unknown parameters: S^* and L. Unfortunately, in the real case of $d_{\max} < L$, the dependence $N(d)$ represents an ambiguous function of S^* and L. That is why their definite determination requires some additional information, for example, obtained from measurements of spectral dependences of the short-circuit current.

Figure 3 presents the experimental dependences $N(d)$ obtained for the BC SC samples from two groups. This figure also shows the theoretical functions $N(d)$ obtained with the use of expression (8) and such values of S^* and L, at which the experimental dependences agree with the theoretical ones. The agreement between the experimental and theoretical dependences is satisfactory.

The experimental spectral dependences of the internal quantum yield for the BC SC samples from the first group with a floating $p-n$ junction near the front surface are given in Fig. 4. The theoretical functions are constructed with the use of expression (3) and the spectral dependence of the absorption coefficient in silicon $\alpha(\lambda)$ taken from work [8], where this dependence was determined at various temperatures. The spectral dependence $\alpha(\lambda)$ obtained in [8] at 300 K can be numerically approximated by the expression

$$\log(\alpha(\lambda)) = 306.91 - 25.649\lambda^{-1} - 1399.55\lambda +$$

$$+3403.54\lambda^2 - 4782.3\lambda^3 + 3901.23\lambda^4 -$$

$$-1713.98\lambda^5 + 311.596\lambda^6 \;, \tag{9}$$

where the wavelength λ is measured in micrometers.

As one can see from Fig. 4, the use of the value of 250 μm for the diffusion length allows one to match the experimental dependences with the theoretical ones, if the coefficient of light reflection from the backside surface is significant (~ 0.7), and the value of S^* which is determined in this case by the SCR recombination rate is large, which is true at low irradiation levels realized with the use of a monochromator. Without regard for the light reflection from the backside surface, the calculated maximum lies to the left from the experimental one.

The inset in Fig. 4 shows the theoretical spectral dependences of the short-circuit current at various diffusion lengths L. As one can see from the inset, an increase of the diffusion length practically does not affect the position of the maximum of the function $J_{\rm SC}(\lambda)$ but results in a rise of its value.

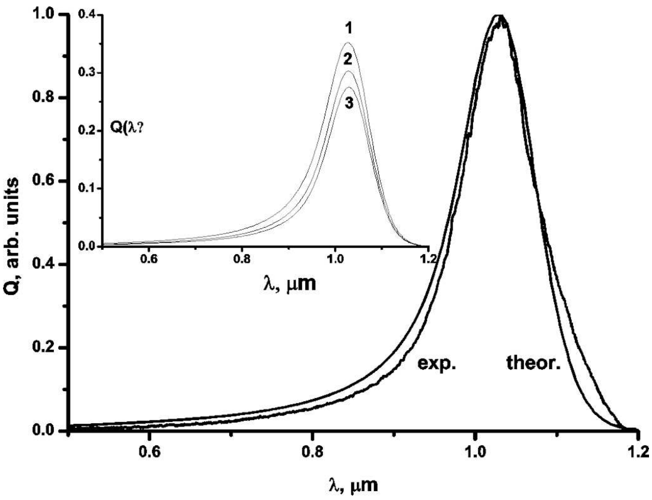

Fig. 4. Experimental and theoretical spectral dependences of the BC SC quantum yield normalized to its maximum value at $R_d = 0.7$, $S^* = 7\times10^4$ cm/s, $L = 250$ μm; in the inset – spectral dependences of the BC SC quantum yield at $R_d = 0.7$, $S^* = 7\times10^4$ cm/s and various L: 500 μm (*1*), 250 μm (*2*), and 500 μm (*3*).

4. Thickness Dependences of BC SC Photoenergy Parameters

Theoretical thickness dependences of such photoenergy parameters as the short-circuit current $I_{\rm SC}$, the open-circuit voltage $V_{\rm OC}$, and the photoconversion efficiency η of BC SCs were simulated, in particular, in [9–11]. The photoconversion efficiency of BC SCs depends most considerably on the thickness dependence of the short-circuit current. In [11], it was shown that, in the case where $d < L$, the thickness dependence of the short-circuit current density of BC SCs $J_{\rm SC}$ under the condition of total light trapping is determined by the formula

$$J_{\rm SC} \cong \frac{J_{\rm gen}}{1 + S^* d/D_a}, \tag{10}$$

where $J_{\rm SC}$ stands for the generation current density in a silicon BC SC for the indicated irradiation conditions, and D_a is the bipolar diffusion coefficient.

In the case of the linearity with respect to the excess concentration of electron-hole pairs (i.e. $\Delta p(x = w) < n_0$, where n_0 is the equilibrium concentration of majority carriers in the BC SC base), one can calculate the short-circuit current density in BC SCs with the use of expression (3), by taking the light reflection from the front surface and its incomplete absorption in the semiconductor into account. In particular, under the AM0 conditions, for which the solar radiation spectrum can be approximated to a good accuracy by the blackbody radiation with a temperature of 5800 K, the short-circuit current density of a silicon BC SC at room temperature is described by the expression

$$J_{\rm SC} \cong 0.656 \int\limits_0^{1,13} \frac{(1 - R_s(\lambda))Q(\lambda)}{\lambda^4(\exp(2,494/\lambda) - 1)} d\lambda, \tag{11}$$

where $R_s(\lambda)$ is the coefficient of light reflection from the front surface, while the irradiation wavelength λ and the current density are measured in micrometers and A/cm^2, respectively.

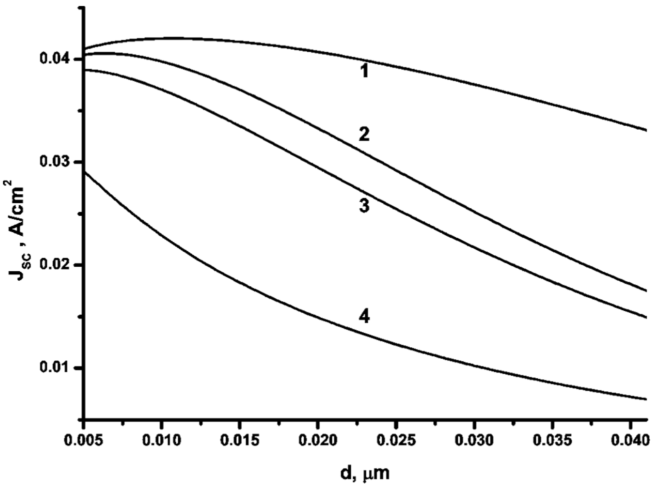

Fig. 5. Calculated thickness dependences of the BC SC short-circuit current under the AM0 conditions. $R_d = 0.7$; $L = 500$ μm (*1*), 250 μm (*2*—*4*); $S^* = 10$ cm/s (1,2), 10^2 (*3*), and 10^3 (*4*)

Figure 5 demonstrates the theoretical thickness dependences of the short-circuit current density in BC SCs obtained with the use of expression (11) in the case where $R_s(\lambda) = 0.1$. As one can see from Fig. 5, these dependences have a maximum at sufficiently small values of S^* (see curves *1, 2*). Moreover, its position shifts toward lower thicknesses d with increase in the value of S^* and with decrease in the diffusion length L. In the given case, the existence of the maximum is due to the competition of two processes. As the thickness decreases, the total recombination in the quasineutral volume falls, due to which the value of $J_{\rm SC}$ must increase. At the same time, the number of electron-hole pairs generated by Sun's light also decreases because of a smaller absorption, which favors a reduction of $J_{\rm SC}$. Depending on which of the indicated factors dominates, we obtain either an increase or a decrease of the short-circuit current with decrease in the thickness. However, in the case of large S^*, where the losses due to the surface recombination play a dominant role, the region, where $J_{\rm SC}$ decreases with increase in d, is absent (curve *4*). In this case, the short-circuit current grows with decrease in the thickness even at very small thicknesses (~ 10 μm). It is explained by the fact that, with decrease in the thickness at $d < L$, the majority of generated pairs will move to the backside surface characterized by a very high "recombination rate" in the short-circuit mode. Therefore, the value of $J_{\rm SC}$ will rise.

In the case of total light trapping, where $J_{\rm SC}$ satisfies expression (10), no reduction of the short-circuit current at small d is present, whereas its value at $d \approx L$ exceeds that obtained from Eq. (11).

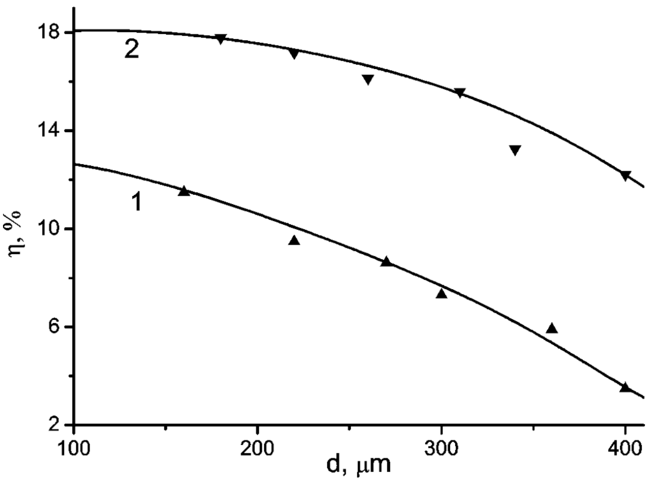

Fig. 6. Experimental (dots) and theoretical (solid lines) thickness dependences of the BC SC photoconversion efficiency under AM1.5 conditions for the samples from the first (*1*) and second (*2*) groups. $R_d = 0.7$, $L = 500$ μm, $S_0 = 70$ cm/s, $d_0 = 70$ μm (*1*), $R_d = 0.7$, $L = 250$ μm, $S_0 = 350$ cm/s, $d_0 = 40$ μm (*2*)

As was noted above, when searching for the thickness dependence of the BC SC photoconversion efficiency η, the latter is mainly determined by the function $J_{\rm SC}(d)$. Therefore, for a unit-area SC under the AM0 conditions, we can write

$$\eta_{\rm AM0} \approx J_{\rm SC}(d) V_{\rm OC} FF/0.135 \ , \qquad (12)$$

where FF is the occupation factor of the current-voltage characteristic, and the factor of 0.135 W/cm^2 is the irradiation power under the AM0 conditions.

It is worth noting that, under the AM1.5 spectral conditions, formula (12) turns into the expression

$$\eta_{\rm AM1.5} \approx 0.8 \ J_{\rm SC}(d) V_{\rm OC} FF/0.1, \qquad (13)$$

where we took a decrease of both the limit short-circuit current and the irradiation power under the AM1.5 conditions into account.

Figure 6 presents the experimental thickness dependences of the photoconversion efficiency for the BC SC samples from the first and second groups at room temperature under AM1.5 conditions. The theoretical dependences $\eta(d)$ were calculated using relation (13), i.e, they were obtained with regard for the thickness dependence $J_{\rm SC}(d)$ determined with the use of (10) and average values of $V_{\rm OC}$ and FF. As one can see from Fig. 6, the experimental thickness dependences of the photoconversion efficiencies agree with the calculated ones, which justifies the use of the thickness dependence $J_{\rm SC}(d)$ alone in (13). It is worth noting that the agreement is reached using the diffusion lengths for the samples from the first and second groups that were determined with the help of expression (8) (see Fig. 3).

In addition, it turned out that the agreement between the experimental and theoretical functions $\eta(d)$ can be reached only under the assumption that the effective surface recombination rate depends on the thickness, namely, it was supposed that it changes according to the law

$$S^*(d) = S_0 \exp\left(\frac{d - d_{\max}}{d_0}\right), \tag{14}$$

where d_0 is some parameter that determines a decrease of S^* with decrease in the thickness. In spite of small initial values of η for the samples from the first group at $d = 400$ μm, which is related to the insufficiently large diffusion length, we could realize the efficiency $\eta \approx 12\%$ by reducing the thickness of the studied sample to 160 μm and minimizing the surface recombination rate due to the formation of a microporous silicon layer. In the samples from the second group having the twice larger diffusion length, the thinning results in the efficiency $\eta \approx 18\%$ (Fig. 6).

5. Conclusions

It is shown that, under certain conditions, the experimental investigation of the thickness dependences of the short-circuit current of BC SCs in the case of strong light absorption and their comparison with the theoretically calculated functions allow one to determine both the surface recombination rate and the diffusion length of minority carriers.

It is established that the experimental spectral dependences of the short-circuit current of the studied BC SC samples agree with the theoretical ones only with regard for the effect of light reflection from the backside surface. If the value of S^* is high, then the position of their maximum practically does not depend on the diffusion length L, whereas the value of J_{SC} in the maximum significantly depends on L.

It is shown that, as the thickness decreases, the photoconversion efficiency in the studied BC SC samples considerably grows. Moreover, we have obtained a good agreement between the experimental and theoretical dependences of $\eta(d)$.

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ЗАЛЕЖНОСТІ ФОТОЕЛЕКТРИЧНИХ ХАРАКТЕРИСТИК КРЕМНІЄВИХ СОНЯЧНИХ ЕЛЕМЕНТІВ З ТИЛОВОЮ МЕТАЛІЗАЦІЄЮ ВІД ТОВЩИНИ

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Р е з ю м е

Експериментально та теоретично досліджено товщинні залежності квантового виходу фотоструму та фотоенергетичних параметрів кремнієвих сонячних елементів з тиловою металізацією (СЕТМ). Мінімізацію швидкості поверхневої рекомбінації (ШПР) на освітленій поверхні в них досягнуто за рахунок створення шарів мікропористого кремнію. Запропоновано метод знаходження ШПР та довжини дифузії неосновних носіїв заряду з товщинних залежностей квантового виходу фотоструму в умовах сильного поглинання світла. Виконані дослідження дозволили встановити, що потоншення зразків СЕТМ за умови мінімізації ШПР дозволяє реалізувати достатньо великі значення ефективності фотоперетворення. Показано також, що узгодження експериментальних спектральних залежностей квантового виходу фотоструму в досліджених СЕТМ з теоретичними може бути досягнуте лише за умови врахування коефіцієнта відбиття світла від тилової поверхні.