ISSN 2079-1704. Хімія, фізика та технологія поверхні. 2017. Т. 8. № 3. С. 322-332

UDC 538.935

doi: 10.15407/hftp08.03.322

V.F. Onyshchenko, L.A. Karachevtseva

EFFECTIVE MINORITY CARRIER LIFETIME AND DISTRIBUTION OF STEADY-STATE EXCESS MINORITY CARRIERS IN MACROPOROUS SILICON

V. Lashkaryov Institute of Semiconductor Physics of National Academy of Sciences of Ukraine
41 Nauki Ave., Kyiv, 03680, Ukraine, E-mail: lakar@isp.kiev.ua

We have obtained a simple expression that determines the effective minority carrier lifetime in macroporous silicon with periodic arrangement of infinitely long macropores as a function of bulk lifetime, surface recombination velocity of minority carriers, pore radius and the distance between the centers of macropores. This expression can be applied also to macroporous silicon with randomly distributed pores by replacing the pore radius and the distance between the centers of macropores with their average values. The distribution of steady-state excess minority carriers in macroporous silicon is calculated for the analytical model proposed by us. The calculation is made for the case when both the outer surface of macroporous silicon and the bottom of pores are illuminated with light. We observed two peaks of the distribution of steady-state excess minority carriers in macroporous silicon near the surfaces illuminated with light of wavelength 0.95 μm. At the same time, if macroporous silicon was illuminated with light with the wavelength of 1.05 μm, we observed only one maximum in the distribution function of the excess minority carriers, in spite of the fact that the pore bottom was also illuminated with light. It is shown that the distribution of excess minority carriers in macroporous silicon with through pores is similar to the distribution in single crystal silicon. But in this case, the effective lifetime of minority charge carriers in the effective medium of macroporous silicon, which includes silicon and the surface of pores, corresponds to the bulk minority-carrier lifetime in monocrystalline silicon.

Keywords: *effective minority carrier lifetime, excess minority carrier distribution, macroporous silicon*

INTRODUCTION

Macroporous silicon is a promising material for the development of 2D photonic structures with the required geometry and large effective surface [1, 2]. This determines optical, electro-optical and electrical characteristics of macroporous silicon structures [3–5]. In view of the potential barrier on a macropore surface, one should take into account recharging of the local surface centers at the energies below that of the indirect interband transition. The photo-luminescence of polyethyleneimine with carbon multiwall nanotubes on macroporous Si with a microporous layer is about six times more intense in comparison with substrates c-Si, macroporous Si and oxidized macroporous Si [6, 7]. The effective conductivity and photoconductivity in macroporous silicon were calculated and measured. Their values go down as the concentration and volume fraction of macropores increase [5]. A reduction in the thickness of the space charge region (SCR) at small macropore diameters was taken into account in [5]. Both theoretical and experimental temperature dependences of photovoltage generation [8] as well as the mechanisms of photocarrier transport through a barrier in the SCR in macroporous silicon [9] at photon energies comparable to that of the indirect interband transition in silicon were investigated. The increase in absorption of electromagnetic radiation and photoconductivity dependence on the angle of incidence of electromagnetic radiation were found in [10]. In [11] the temperature dependence of photoconductivity relaxation in macroporous silicon was measured, as well as the effective relaxation time and its temperature dependence were calculated. Gas and biological sensors are developed on the basis of porous silicon with CMOS-compatible manufacturing [12, 13]. Macroporous silicon is used as a solar cell [14, 15]. The effective lifetime of light-generated carriers in macroporous thin-film Si absorbers decreases owing to recombination at large areas of pore surface [16, 17]. An analytical model for the effective carrier lifetimes of surface-passivated macroporous crystalline silicon was derived in [18, 19]. That model determined the effective minority carrier lifetime in macroporous silicon as a function of bulk lifetime, surface passivation, and pore morphology.

The present paper provides a derivation of a simple expression for the effective minority carrier lifetime in macroporous silicon with periodic arrangement of infinitely long pores. We also determine the distribution of steady-state excess minority carriers in macroporous silicon.

THE MODEL OF EXCESS MINORITY CARRIER DISTRIBUTION IN MACROPOROUS SILICON WITH PERIODIC ARRANGEMENT OF INFINITELY LONG MACROPORES

The steady state minority carrier diffusion for *n*-type silicon is determined by equation:

$$D_p\nabla^2(\delta p) - \frac{\delta p}{\tau_b} + g_p = 0. \quad (1)$$

Here D_p is the minority carrier diffusion coefficient, δp is the distribution function of the steady-state excess minority carrier concentration dependent on radius vector r, g_p is the excess minority carrier generation rate, τ_b is the minority carrier bulk lifetime. The boundary condition for differential Eq. (1) is

$$g_s = e^{-1} j_p(0) + s_p \delta p(0)\,. \quad (2)$$

Here e is the elementary electric charge, g_s is the rate of surface generation of excess charge carriers, $j_p(0)$ is the minority carrier current density at the sample surface, s_p is the surface recombination velocity of minority carriers, $\delta p(0)$ is the excess minority carrier concentration at the sample surface.

First of all, let us solve the problem of distribution of steady-state excess charge carriers as a function of the radius vector r in the cylindrical unit cell of macroporous silicon with periodic arrangement of infinitely long macropores (see Fig. 1 *c*).

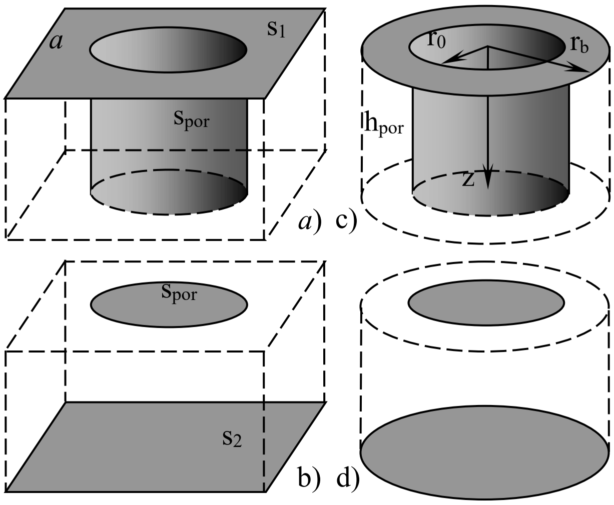


Fig. 1. A unit cell: *a* – and *b* – for the macropores arranged in a square lattice, *c* and *d* a cylindrical coordinate system. The macroporous silicon layer is *a* and *c*, the single crystal substrate is *b* and *d*. The surfaces where recombination occurs are shown by solid lines and are filled. The boundaries of the unit cells are shown by dashed lines

The minority carrier diffusion Eq. (1) in the cylindrical coordinates for the cylindrical unit cell of macroporous silicon with periodic arrangement of the infinitely long macropores is

$$D_p\left[\frac{\partial^2 \delta p(r)}{\partial r^2} + \frac{1}{r}\frac{\partial \delta p(r)}{\partial r}\right] - \frac{\delta p(r)}{\tau_b} + g_p = 0\,. \quad (3)$$

Here g_p is the rate of spatially homogeneous generation of excess minority carriers, $\delta p(r)$ is the distribution function of steady-state excess minority carrier concentration as a function of the radius vector r. The general solution of the diffusion Eq. (3) is

$$\delta p(r) = g_p\tau_b(1 + C_1 I_0(R) - C_2 K_0(R)), \quad (4)$$

where $R = r/L_p$, $L_p = (D_p\tau_b)^{1/2}$ is the minority carrier diffusion length, C_1 and C_2 are constants, $I_\alpha(R)$ and $K_\alpha(R)$ are the modified Bessel functions, α is the order of the Bessel function. The boundary condition on the surface of cylindrical unit cell (Fig. 1 *c*) is

$$D_p \left.\frac{d\delta p(r)}{dr}\right|_{r=rb} = D_p(C_1 I_1(R_b) - C_2 K_1(R_b)) = 0\,, \quad (5)$$

where is $R_b = r_b/L_p$ and r_b is the radius of cylindrical unit cell. The boundary condition on the surface of macropore wall (Fig. 1 *c*) is

$$D_p \left.\frac{d\delta p(r)}{dr}\right|_{r=r0} = -s_{por}\delta p(r_0)\,, \quad (6)$$

where r_0 is the pore radius, s_{por} is the surface recombination velocity of minority carriers on the surface of macropore walls. From Eqs. (4) and (6) it follows that

$$C_1 I_1(R_0) - C_2 K_1(R_0) = -S(1 + C_1 I_0(R_0) - C_2 K_0(R_0)), \quad (7)$$

where $R_0 = r_0/L_p$ and $S_{por} = s_{por}L_p/D_p$ are dimensionless quantities. The constants C_1 and C_2 may be determined from Eqs. (5) and (7). The solution of Eq. (1) is the distribution function of steady-state excess minority carrier concentrations as a function of the radius vector *r*

$$(\delta p)_s(r) = g_p\tau_b\left(1 - \frac{S_{por}(I_1(R_b)K_0(R) + K_1(R_b)I_0(R))}{I_1(R_b)(K_1(R_0) + S_{por}K_0(R_0)) - K_1(R_b)(I_1(R_0) - S_{por}I_0(R_0))}\right), \quad (8)$$

where $R_0 = r_0/L_p$ and $S_{por} = s_{por}L_p/D_p$ are dimensionless quantities.

EFFECTIVE MINORITY CARRIER LIFETIME IN MACROPOROUS SILICON

The average concentration of steady-state excess minority carriers in the cylindrical unit cell is

$$\overline{(\delta p)_S} = \frac{g_p}{\tau_{eff}} = \frac{2\pi}{\pi r_b^2 - \pi r_0^2}\int_{r0}^{rb}\delta p(r)rdr\,, \quad (9)$$

where τ_{eff} is the effective minority carrier lifetime. Using Eqs. (8) and (9) as well as $\int_{r0}^{rb} K_0(R)rdr = -L_b r K_1(R)\Big|_{r0}^{rb}$ and $\int_{r0}^{rb} I_0(R)rdr = L_b r I_1(R)\Big|_{r0}^{rb}$, one can found the average concentration of steady-state excess minority carriers in the cylindrical unit cell:

$$\overline{(\delta p)_S} = g\tau_b\left(1 - \frac{2s\tau_b r_0(I_1(R_b)(K_1(R_0) - K_1(R_b)I_1(R_0))/(r_b^2 - r_0^2)}{I_1(R_b)(K_1(R_0) + SK_0(R_0)) - K_1(R_b)(I_1(R_0) - SI_0(R_0))}\right). \quad (10)$$

If R_0, $R_b < 0.1$, we can replace the cylindrical modified Bessel functions by the functions that can be written as $I_0(R) > 1$, $I_1(R) > R/2$, $K_0(R) > -\ln(R)$ and $K_1(R) > 1/R$. Then it is possible to present Eqs. (8) and (10) as

$$(\delta p)_S(r) = g\tau_b\left(1 - \frac{-\frac{r_b}{2L_p}\frac{sL_p}{D_p}\ln(\frac{r}{L_p}) + \frac{sL_p}{D_p}\frac{L_p}{r_b}}{\frac{r_b}{2r_0} - \frac{r_b}{2L_p}\frac{sL_p}{D_p}\ln(\frac{r_0}{L_p}) - \frac{r_0}{2r_b} + \frac{L_p}{r_b}\frac{sL_p}{D_p}}\right), \quad (11)$$

$$\overline{(\delta p)_S} = g\tau_b\left(1 - \frac{2s\tau_b r_0(\frac{r_b}{2r_0} - \frac{r_0}{2r_b})\frac{1}{r_b^2 - r_0^2}}{\frac{r_b}{2r_0} - \frac{r_b}{2L_p}\frac{sL_p}{D_p}\ln(\frac{r_0}{L_p}) - \frac{r_0}{2r_b} + \frac{L_p}{r_b}\frac{sL_p}{D_p}}\right). \quad (12)$$

One can neglect the member with logarithm in Eqs. (11) and (12) because $r_b s\cdot\ln(r_0/L_p)/(2D_p) > 10^{-5}$ and $r_b s\cdot\ln(r/L_p)/(2D_p) > 10^{-5}$, when s<1 m/s. Then we reduced the expressions in parentheses in Eqs. (11) and (12) to a common denominator, made reduction of fractions and turned over the fractions. The Eqs. (11) and (12) can be brought to the single expression:

$$\frac{g}{(\delta p)_S} = \frac{g}{(\delta p)_S(r)} = \frac{1}{\tau_{eff}} = \frac{1}{\tau_b}\left(\frac{\frac{r_b^2 - r_0^2}{2r_0 r_b} + \frac{\tau_b s}{r_b}}{\frac{r_b^2 - r_0^2}{2r_0 r_b}}\right) \qquad (13)$$

or

$$\frac{1}{\tau_{eff}} = \frac{1}{\tau_b} + \frac{2sr_0}{r_b^2 - r_0^2}\,. \qquad (14)$$

Let us obtain a simple expression for determination of effective minority carrier lifetime in a cylindrical unit cell. If both the numerator and denominator on the right of Eq. (14) are multiplied by πh_{por}, then we have

$$\frac{1}{\tau_{eff}} = \frac{1}{\tau_b} + \frac{2\pi r_0 s}{a^2 - \pi r_0^2}\frac{h_{por}}{h_{por}}\,, \qquad (15)$$

where h_{por} is the depth of macropore and a is the average distance between the centers of macropores (see Fig. 1 *c*). (The area πr_b^2 of a circle is replaced by the square face area a^2 of a unit cell – see Fig. 1 *a*). In the general case Eq. (15) can be written as

$$\frac{1}{\tau_{eff}} = \frac{1}{\tau_b} + \frac{sS_{spor}}{V_{cb} - V_{por}}\,, \qquad (16)$$

where V_{cb} is the unit cell volume, V_{por} is the pore volume and S_{spor} is the macropore surface area. Eq. (10) is equivalent to Eq. (16) provided $R_0, R_b < 0.1$.

THE MODEL OF EXCESS MINORITY CARRIER DISTRIBUTION IN MACROPOROUS SILICON IN THE CASE OF SPATIALLY INHOMOGENEOUS GENERATION OF CHARGE CARRIERS

Let us now solve the problem of the distribution of steady-state excess charge carriers through the depth of cylindrical unit cell of macroporous silicon with periodic arrangement of macropores (see Fig. 1 *c*). The effective minority carrier lifetime in the unit cell of macroporous silicon with periodic arrangement of the infinitely long macropores will be applied. The minority carrier diffusion equation for the one-dimensional case under steady state condition for macroporous *n*-silicon in the *x*-direction (parallel to the pores) is

$$D_p\frac{\partial^2(\delta p(x))}{\partial x^2} - \frac{\delta p(x)}{\tau_{eff}} + g_{0p}(\alpha)\exp(-\alpha x) = 0\,. \qquad (17)$$

Here $\delta p(x)$ is the distribution function of the excess minority carrier concentration in the *x*-direction, α is the absorption coefficient of silicon, $g_{0p}(\alpha)$ is the generation rate of excess minority charge carriers at the illuminated surface, and $(\delta p)_s(r)$ is taken from Eq. (8). The origin of coordinates is chosen on the illuminated surface of macroporous silicon. The *x*-axis is directed into the macropore depth. The generation of excess minority carriers is spatially inhomogeneous due to optical absorption in silicon. The general solution of the second-order non-homogeneous linear differential Eq. (17) is

$$\delta p(x) = C_1\cosh\left(\frac{x}{L_{eff}}\right) - C_2\sinh\left(\frac{x}{L_{eff}}\right) - \frac{g_{0p}(\alpha)\alpha\tau_{eff}\exp(-\alpha x)}{(\alpha L_{eff})^2 - 1}\,, \qquad (18)$$

where C_1 and C_2 are constants and $L_{eff} = \sqrt{D_p\tau_{eff}}$ is the effective minority carrier diffusion length in macroporous silicon (between the surfaces of macropore walls).

The distribution functions of the steady-state excess minority carrier concentration (Eq. (18)) in silicon between the surfaces of macropore walls (macroporous silicon, see Fig. 1 *c*) and for single crystal silicon under the macropores (the single crystal substrate, see Fig. 1 *d*) are

$$\delta p_1(x) = C_1\cosh(X_1) - C_2\sinh(X_1) - \delta p_{g1}(x)\,, \qquad (19)$$

$$\delta p_2(x) = C_3\cosh(X_2) - C_4\sinh(X_2) - \delta p_{g2}(x)\,. \qquad (20)$$

Here $\delta p_{g2}(x) = \frac{g_0\alpha\tau_2\left[(1-P)\exp(-\alpha x) + P\exp(-\alpha(x-h_1))\right]}{(\alpha L_2)^2 - 1}$,

$\delta p_{g1}(x) = \frac{g_0\alpha\tau_1\exp(-\alpha x)}{(\alpha L_1)^2 - 1}$, $X = \frac{x}{L_p}$, $X_1 = \frac{x}{L_1}$, $X_2 = \frac{x}{L_2}$, $L_1 = \sqrt{D_p\tau_{eff}}$, $L_2 = \sqrt{D_p\tau_b}$, $h_1 = h_{por}$ is the macropore depth and $P = \pi D^2/(4a^2)$ is the pore volume fraction.

The boundary conditions for the surfaces having surface recombination velocities s_1 and s_2 (see Figs. 1 *a* and 1 *b*) are

$$D_p \left. \frac{d\delta p_1(x)}{dx} \right|_{x=0} = s_1 \delta p_1(x)\big|_{x=0} \tag{21}$$

$$D_p \left. \frac{d\delta p_2(x)}{dx} \right|_{x=h2} = -s_2 \delta p_2(x)\big|_{x=h2}. \tag{22}$$

The excess minority carrier concentrations calculated for the macroporous layer and single crystal substrate must be equal at the plane passing through the bottom of macropores:

$$\delta p_1(h_1) = \delta p_2(h_1). \tag{23}$$

The excess minority carrier currents flowing within the macroporous layer and single crystal substrate must be equal at the plane passing through the bottom of the macropores, therefore

$$D_p \left((1-P)\frac{d\delta p_1(x)}{dx} + \frac{d\delta p_2(x)}{dx} \right)\Bigg|_{x=h1} - P s_{por} \delta p(h_1) = 0, \tag{24}$$

where s_{por} is the surface recombination velocity of minority carriers on the surface of macropores (see Fig. 1 *b*).

The unknown coefficients C_1, C_2, C_3 and C_4 can be found from the system of Eqs. (19–24) that can be written more compactly as

$$C_1 S_1 + C_2 - \Delta p_{g1}(0)(\alpha L_1 + S_1) = 0, \tag{25}$$

$$\begin{aligned} &C_3[\sinh(H_2) + S_2\cosh(H_2)] - C_4[S_2\sinh(H_2) + \\ &+ \cosh(H_2)] + \delta p_{g2}(h_2)(\alpha L_2 - S_2) = 0, \end{aligned} \tag{26}$$

$$\begin{aligned} &[C_1\sinh(H_1) - C_2\cosh(H_1)]S_{1por}^{-1}(1-P) + \\ &+ C_3\left[P\cosh(H_{12}) - S_{2por}^{-1}\sinh(H_{12})\right] + \\ &+ C_4\left[P\sinh(H_{12}) + S_{2por}^{-1}\cosh(H_{12})\right] + \\ &+ \alpha D\delta p_{1g}(h_1) - \delta p_{2g}(h_2)(S_{2\alpha por}^{-1} + P) = 0, \end{aligned} \tag{27}$$

$$\begin{aligned} &C_1\cosh(H_1) - C_2\sinh(H_1) - C_3\cosh(H_{12}) + \\ &+ C_4\sinh(H_{12}) - \delta p_{1g}(h_1) - \delta p_{2g}(h_2) = 0. \end{aligned} \tag{28}$$

Here h_2 is the thickness of macroporous silicon, the dimensionless thicknesses and surface recombination velocities are $H_1 = \frac{h_1}{L_1}$, $H_2 = \frac{h_2}{L_2}$, $H_{12} = \frac{h_1}{L_2}$, $S_1 = \frac{s_1 L_1}{D_p}$, $S_2 = \frac{s_2 L_2}{D_p}$, $S_{1por} = \frac{s_{por} L_1}{D_p}$, $S_{2por} = \frac{s_{por} L_2}{D_p}$ and $S_{2\alpha por} = \frac{s_{por}}{\alpha D_p}$.

THE RESULTS OF CALCULATION OF EXCESS MINORITY CARRIER DISTRIBUTION IN MACROPOROUS SILICON IN THE CASE OF SPATIALLY INHOMOGENEOUS GENERATION OF CHARGE CARRIERS

We calculated and analyzed the concentration distribution of steady-state excess minority carriers in macroporous silicon in the case of spatially inhomogeneous generation of charge carriers. The macroporous silicon was illuminated with light of wavelengths 0.95, 1.05 μm. The light was incident perpendicularly to the surface of macroporous layer. Part of light entered into macropores and illuminated a single crystal substrate because the macropore bottom is a part of the single crystal substrate surface. The average macropore diameter was 1 μm. The average distance between the macropore centers was 2 μm which corresponded to the average concentration of macropores of $2.5 \cdot 10^7$ cm^{-2}. Volume fraction of the macropores is 0.2. Surface recombination velocity is 1 m·s^{-1}. The bulk minority carrier lifetime was 10 μs. The minority carrier diffusion coefficient in *n*-silicon was 12 cm·s^{-1}. The steady-state excess minority carrier concentration in macroporous silicon was normalized to its maximum value.

We performed calculation and analysis for three cases. In the first case, we analyzed macroporous silicon having substrate thickness of 300 μm and depth of macropores from 0 to 200 μm. In the second case, we analyzed macroporous silicon having thickness from 100 to 600 μm and 100 μm depth of macropores. In the third case, we investigated 500 μm thick macroporous silicon with macropores depth from 0 to 500 μm.

CALCULATION FOR CASE 1: THE MACROPORES DEPTH FROM 0 TO 200 μm AND THE SUBSTRATE THICKNESS OF 300 μm

Fig. 2 shows the calculated distribution functions of the steady-state excess minority carrier concentration in macroporous silicon at different pore depths. The curves 1–5 correspond to macropore depths of 0, 10, 50, 100, 150, and 200 μm. The substrate thickness is 300 μm. The steady-state excess minority carrier concentrations decrease exponentially in single crystal silicon with thickness of 300 μm (see Fig. 2, curves 1). This decrease is caused by absorption of light in macroporous silicon (Fig. 2 *a*) or by diffusion of charge carriers toward the surface of recombination (Fig. 2 *b*). If the macropores with depth of 10 μm are etched in single crystal with thickness of 310 μm, then the steady-state excess minority carrier concentration is reduced by increasing the surface of recombination formed with macropores (see Fig. 2, curves 2).

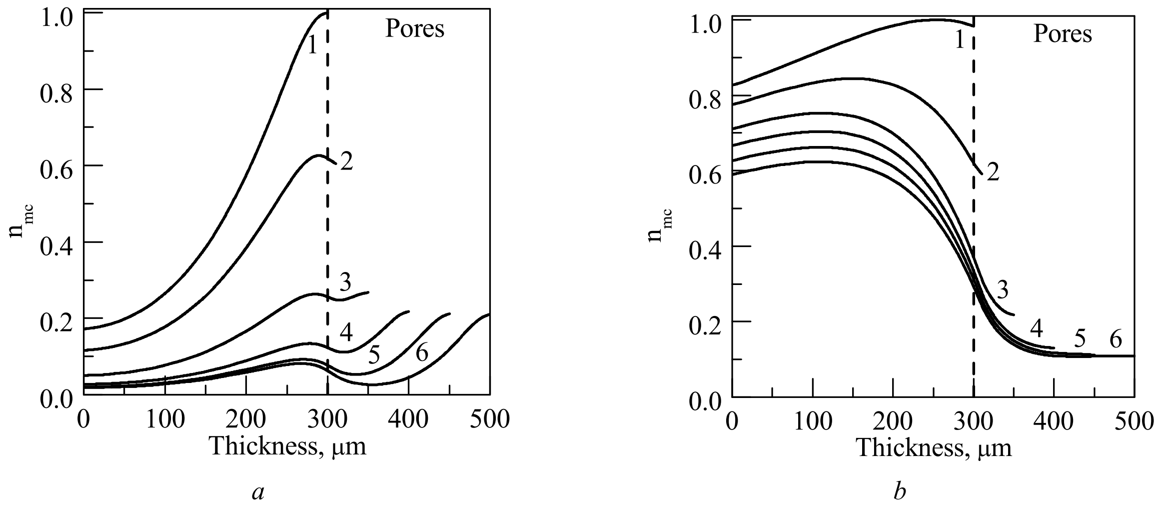


Fig. 2. The distribution function of the normalized steady-state excess minority carriers concentration n_{mc} in macroporous silicon. Macroporous silicon is illuminated with light of wavelengths 0.95 (*a*) and 1.05 μm (*b*). The depths of macropores are 0 (*1*), 10 (*2*), 50 (*3*), 100 (*4*), 150 (*5*) and 200 μm (*6*). The thickness of single crystal silicon substrate is 300 μm

We also see maxima of the distribution functions of steady-state excess minority carrier concentration. A similar maximum is observed in a single crystal silicon at high surface recombination velocity. The second maximum of the concentration distribution of the steady-state excess minority carriers appears only when macroporous silicon is illuminated with light of wavelength 0.95 μm (see Fig. 1 *a*, curves 3–6). The maxima of the concentration distribution of steady-state excess minority carriers are near the illuminated surfaces, as seen in Fig. 2. These maxima are due to diffusion of excess charge carriers either from the regions with higher concentration into those with lower concentration or to the surfaces of recombination. As seen in Fig. 2 *a*, the concentration of excess charge carriers increases in the macroporous layer because the excess charge carriers diffuse from the single crystal substrate illuminated with light of wavelength 0.95 μm into the macroporous layer where their concentration is lower. The second maximum of the distribution function of steady-state excess minority carrier concentration does not appear when macroporous silicon is illuminated with light of wavelength 1.05 μm because light of this wavelength is weakly absorbed and generation of excess carriers in the sample is almost homogeneous (Fig. 1 *b*, curves 2–6). In this case, the main role is played by bulk recombination of the excess carriers in the single crystal substrate and recombination of the excess carriers on the surface macropores in the macroporous layer.

The space between macropores in the macroporous layer is characterized by the effective minority carrier lifetime because in this case recombination occurs both in the volume between macropores and on the surface macropores. The concentration distribution of excess carriers in the macroporous layer remains almost unchanged at increasing thickness of the macroporous layer and constant thickness of the single crystal substrate (Fig. 2 *b*, curves 4–6). This is because the diffusion of excess charge carriers from the single crystal substrate cannot deliver a greater number of charge carriers.

CALCULATION FOR CASE 2: THE MACROPORES DEPTH OF 100 μm AND THE MACROPOROUS SILICON THICKNESS FROM 100 TO 600 μm

Fig. 3 shows the calculated distribution function of the steady-state excess minority carrier concentrations in macroporous silicon illuminated with light of wavelengths 0.95 (*a*) and 1.05 μm (*b*). The macropores depth is 100 μm. Curves 1–6 correspond to macroporous silicon with thicknesses of 100, 200, 300, 400, 500, and 600 μm.

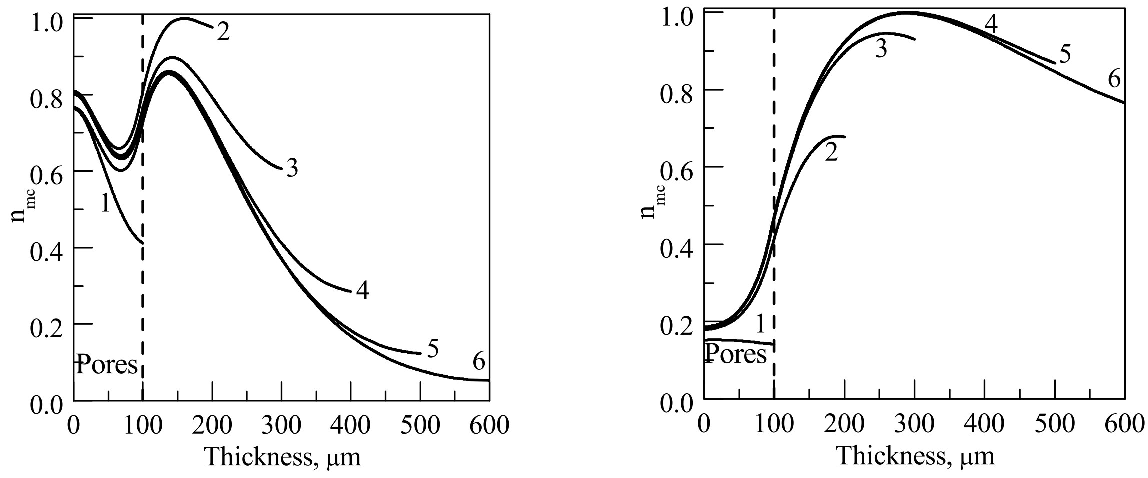


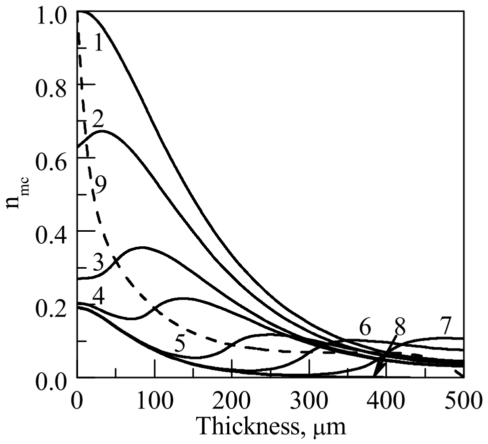
Fig. 3. The distribution function of the normalized steady-state excess minority carriers concentration n_{mc} in macroporous silicon of thickness 100 (*1*), 200 (*2*), 300 (*3*), 400 (*4*), 500 (*5*), and 600 μm (*6*). Macroporous silicon is illuminated with light of wavelengths 0.95 (*a*) and 1.05 μm (*b*)

The excess minority carrier distributions shown in Fig. 3 *a* and Fig. 3 *b* are very different. The distribution of excess minority carriers in macroporous silicon with through pores is similar to that in single crystal silicon (see Fig. 3 *a*, curve 1). But in this case the effective minority carrier lifetime in macroporous silicon corresponds to the bulk lifetimes of minority carriers in single crystal silicon. The distribution function of excess minority carriers in macroporous silicon on a single crystal substrate has another maximum due to additional generation of excess charge carriers at the bottom of macropores (see Fig. 3 *a*, curve 2). If the thickness of single crystal substrate is more than 100 μm, then the second maximum decreases because excess charge carriers diffuse into the macroporous layer and single crystal substrate bulk. Figures 2 *b* and 3 *b* show that the concentration of excess minority carriers in the macroporous layer is much less than that in the single crystal substrate when macroporous silicon is illuminated with light of wavelength 1.05 μm. Electromagnetic radiation of wavelength 1.05 μm is weakly absorbed, so generation of excess charge carriers weakly decreases with distance according to the exponential law. In this case, the concentration of excess minority carriers is determined by both the effective minority carrier lifetime in macroporous silicon and the bulk lifetime of minority carriers in the single crystal substrate. The effective minority carrier lifetime in macroporous silicon is less than the bulk lifetime of minority carriers in the single crystal substrate with higher concentration of minority carriers.

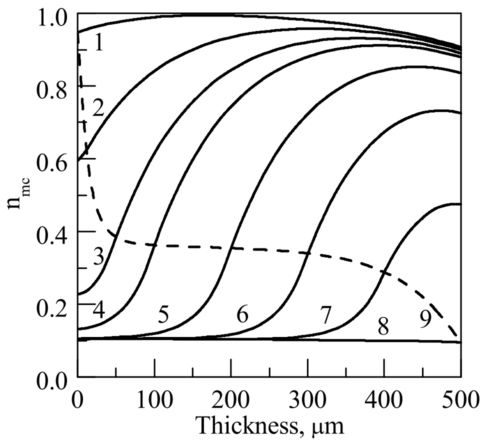
We must also take into account diffusion of the excess charge carriers from the single crystal substrate into macroporous layer to the macropores surfaces where recombination occurs. This diffusion is caused by the concentration gradient of excess charge carriers that appears not only by recombination at the macropores surfaces but also due to illumination of the single crystal substrate through the bottoms of macropores. Actually generation of the excess charge carriers occurs within the material, and then they diffuse into the macroporous layer and toward the opposite surface of the single crystal substrate. The distribution function of the excess charge carriers has no other maximum when macroporous silicon is illuminated with light of wavelength 1.05 μm (see Fig. 3 *b*). The maximum is not observed because generation of excess charge carriers in macroporous silicon is almost homogeneous, and illumination of the macropores bottoms almost does not affect the homogeneity of generation of excess charge carriers. If the single crystal substrate thickness is increased, then the maximum of concentration of excess minority carriers in the single crystal substrate initially increases (see Fig. 3 *a*, curves 1, 2 and Fig. 3 *b*, curves 1–5) and flattens out (see Fig. 3 *a*, curves 2–6 and Fig. 3 *b*, curve 5). The maximum of concentration of excess minority carriers in the single crystal substrate will grow because the minority carrier lifetime in the single crystal substrate is higher than that in the macroporous layer. The excess charge carriers generated by illumination of the pores bottoms diffuse into both the macroporous layer and less illuminated part of the single crystal substrate. The latter will increase as the thickness of the single crystal substrate grows. The diffusion intensity of the excess charge carriers is determined by the diffusion rate, so the maximum of the distribution function of excess minority carriers remains unchanged if the thickness of single crystal substrate is more than 400 μm.

CALCULATION FOR CASE 3: THE THICKNESS OF MACROPOROUS SILICON IS 500 μm, DEPTHS OF MACROPORES VARIES FROM 0 TO 500 μm

Fig. 4 shows the distribution function of the normalized steady-state concentration of excess minority carriers in 500 μm macroporous silicon with different macropore depths. Macroporous silicon is illuminated with light of wavelengths 0.95 μm (see Fig. 4 *a*) and 1.05 μm (see Fig. 4 *b*). Curve 9 shows the normalized steady-state concentration of excess minority carriers in the depth of macropores. The distribution of the normalized steady-state concentration of excess minority carriers in a single crystal with thickness of 500 μm is shown in Fig. 4 (curve 1).



a



b

Fig. 4. The distribution function of the normalized steady-state excess minority carriers concentration n_{mc} in macroporous silicon with thickness of 500 μm. Macroporous silicon is illuminated with light of wavelengths 0.95 (*a*) and 1.05 μm (*b*). Depth of macropores is 0 (*1*), 10 (*2*), 50 (*3*), 100 (*4*), 200 (*5*), 300 (*6*), 400 (*7*), and 500 μm (*8*). Curve *9* shows the normalized steady-state concentration of excess minority carriers at a macropore depth

The concentration of excess charge carriers decreases sharply in the macroporous layer and the single crystal substrate at macropores depth of 10 μm (see Fig. 4, curves 2).

Figure 4a shows that curves 1 and 2 have the only maximum. The second maximum of the concentration of excess minority carriers appears if the macropores depth is more than 50 μm (see Fig. 4 *a*, curve 3). The first maximum of the concentration exists due to generation of excess charge carriers on the outer surface of the sample and the effective minority carrier lifetime in macroporous silicon. The second maximum of the concentration appears due to generation of excess charge carriers at the bottom of macropores. A minimum exists between the maxima of the concentration of excess carriers; it appears when the macropore depth is more than two effective diffusion lengths of charge carriers in macroporous silicon (see Fig. 4 *a*, curves 3–7). The concentration of excess carriers in the macroporous layer flattens out and does not change (Fig. 4 *a*, curves 4–7). If the size of the macroporous layer or the single crystal substrate is less than the diffusion length, then the concentration of excess charge carriers decreases sharply (Fig. 4, curves 1–3). Figure 4a shows that the concentration of excess carriers (curve 9) firstly decreases as the depth of macropores grows to 250 μm, then flattens out and at last decreases again at the depth of macropores from 350 to 500 μm. Fig. 4 *b* shows that the concentration of excess carriers (curve 9) firstly decreases as the depth of macropores grows to 100 μm, then flattens out and at last decreases again at the depth of macropores from 300 to 500 μm. The concentration of excess minority carriers is greatly reduced in the macroporous layer or the single crystal substrate if their thicknesses are less than the diffusion length (see Fig. 4, curves 1–3, 8).

CONCLUSIONS

We have calculated and analyzed the distribution of concentration of excess minority carriers in macroporous silicon using our analytical model. The distributions of the concentration of excess minority carriers are different at illumination of macroporous silicon by light of wavelengths 0.95 and 1.05 μm. Firstly one and then another maximum of the distribution function of excess minority carriers in macroporous silicon are observed at increasing of the macropores depth in macroporous silicon illuminated with light of wavelength 0.95 μm. The distribution of excess minority carriers in macroporous silicon with through pores is similar to that in single crystal silicon. But in this case the effective minority carrier lifetime in macroporous silicon corresponds to the bulk lifetimes of minority carriers in single crystal silicon. We have shown that the effective minority carrier lifetime in macroporous silicon depends on bulk lifetime and surface recombination velocity of minority carriers as well as on pore radius and the distance between the centers of macropores.

Ефективний час життя неосновних носіїв заряду і стаціонарний розподіл надлишкових неосновних носіїв заряду в макропористому кремнії

В.Ф. Онищенко, Л.А. Карачевцева

Інститут фізики напівпровідників ім. В.Є. Лашкарьова Національної академії наук України
пр. Науки, 41, Київ, 03680, Україна, lakar@isp.kiev.ua

Отримано простий вираз, що визначає ефективний час життя неосновних носіїв заряду в макропористому кремнії з періодичним розташуванням нескінченно довгих макропор в залежності від об'ємного часу життя, швидкості поверхневої рекомбінації неосновних носіїв заряду, радіуса пор і відстані між центрами макропор. Цей вираз може бути застосовано також до макропористого кремнію з випадково розподіленими порами шляхом заміни радіуса пор і відстані між центрами макропор їх середніми значеннями. Для запропонованої нами аналітичної моделі розраховано стаціонарний розподіл надлишкових неосновних носіїв заряду в макропористому кремнії. Розрахунок виконано для випадку, коли як зовнішня поверхня макропористого кремнію, так і дно пор освітлюються світлом. Виявлено два піки в стаціонарному розподілі надлишкових неосновних носіїв в макропористому кремнії поблизу поверхонь, освітлених світлом з довжиною хвилі 0.95 мкм. У той же час, якщо макропористий кремній освітлювався світлом з довжиною хвилі 1.05 мкм ми спостерігали тільки один максимум в функції розподілу надлишкових неосновних носіїв заряду, незважаючи на те, що дно пор також освітлювалось світлом. Показано, що розподіл надлишкових неосновних носіїв заряду в макропористому кремнії з наскрізними порами аналогічний до розподілу в монокристалічному кремнії. Але в цьому випадку ефективний час життя неосновних носіїв заряду в ефективному середовищі макропористого кремнію, яке включає кремній та поверхню пор, відповідає об'ємному часу життя неосновних носіїв заряду в монокристалічному кремнії.

Ключові слова: *ефективний час життя неосновних носіїв заряду, розподіл надлишкових неосновних носіїв заряду, макропористий кремній*

Эффективное время жизни неосновных носителей заряда и стационарное распределение избыточных неосновных носителей заряда в макропористом кремнии

В.Ф. Онищенко, Л.А. Карачевцева

Институт физики полупроводников им. В.Е. Лашкарёва Национальной академии наук Украины
пр. Науки, 41, Киев, 03680, Украина, lakar@isp.kiev.ua

Получено простое выражение, определяющее эффективное время жизни неосновных носителей заряда в макропористом кремнии с периодическим расположением бесконечно длинных макропор в зависимости от объемного времени жизни, скорости поверхностной рекомбинации неосновных носителей заряда, радиуса пор и расстояния между центрами макропор. Это выражение может быть применено также к макропористому кремнию со случайно распределенными порами путем замены радиуса пор и расстояния между центрами макропор их средними значениями. Для предложенной нами аналитической модели рассчитано стационарное распределение избыточных неосновных носителей в макропористом кремнии. Расчет выполнен для случая, когда как внешняя поверхность макропористого кремния, так и дно пор освещаются светом. Выявлено два пика в стационарном распределении избыточных неосновных носителей заряда в макропористом кремнии вблизи поверхностей, освещенных светом с длиной волны 0.95 мкм. В то же время, если макропористый кремний освещался светом с длиной волны 1.05 мкм, мы наблюдали только один максимум в функции распределения избыточных неосновных носителей заряда, несмотря на то, что дно пор также освещалось светом. Показано, что распределение избыточных неосновных носителей заряда в макропористом кремнии со сквозными порами аналогично распределению в монокристаллическом кремнии. Но в этом случае эффективное время жизни неосновных носителей заряда в эффективной среде макропористого кремния, которая включает кремний и поверхность пор, соответствует объёмному времени жизни неосновных носителей заряда в монокристаллическом кремнии

Ключевые слова: *эффективное время жизни неосновных носителей заряда, распределение избыточных неосновных носителей заряда, макропористый кремний*

REFERENCES

1. Birner A., Wehrspohn R.B., Gösele U.M., Busch K. Silicon-based photonic crystals. *Adv. Mater*. 2001. **13**(6): 377.
2. Karachevtseva L.A. Two-dimensional photonic crystals as perspective materials of modern nanoelectronics. *Semiconductor Physics Quantum Electronics & Optoelectronics*. 2004. **7**(4): 430.
3. Glushko A., Karachevtseva L. Photonic band structure of oxidized macroporous silicon. *Opto-Electron. Rev*. 2006. **14**(3): 201.
4. Glushko A., Karachevtseva L. PBG propertiesof three-component 2D photoniccrystals. *Photonics and Nanostructures*. 2006. **4**(3): 141.
5. Onyshchenko V.F., Karachevtseva L.A. Conductivity and photoconductivity of two-dimensionalmacroporous silicon structures. *Ukr. J. Phys.* 2013. **58**(9): 846.
6. Karachevtseva L.A., Kartel M.T., Konin K.P., Lytvynenko O.O., Onyshchenko V.F., Bo Wang Light emitting "polymer-nanoparticles" coatings on macroporous silicon substrates. *Him. Fiz. Tehnol. Poverhni.* 2017. **8**(1): 18.
7. Karachevtseva L.A., Kartel M.T., Lytvynenko O.O., Onyshchenko V.F., Parshyn K.A., Stronska O.J. Polymer-nanoparticle coatings on macroporous silicon matrix. *Adv. Mater. Lett*. 2017. **8**(4): 336.
8. Karachevtseva L., Onyshchenko V., Sachenko A. Photocarrier transport in 2Dmacroporous silicon structures. *Opto-Electron. Rev.* 2010. **18**(4): 394.
9. Onyshchenko V.F., Sachenko A.V., Karachevtseva L.A. Anomalous-sign photo-emf in macroporous silicon at photon energies comparable to that of indirect band-to-band transition. *Ukr. J. Phys.* 2009. **54**(12): 1212.
10. Karachevtseva L., Karas M., Onishchenko V., Sizov F. Surface polaritons in 2D macroporous silicon structures. *Int. J. Nanotechnology*. 2006. **3**(1): 76.
11. Karachevtseva L.A., Onyshchenko V.F., Sachenko A.V. Kinetics of photoconductivity inmacroporous silicon structures. *Ukr. J. Phys.* 2008. **53**(9): 874.
12. Barillaro G., Bruschi P., Pieri F., Strambini L.M. CMOS-compatible fabrication of porous silicon gas sensors and their readout electronics on the same chip. *Phys. Status. Sol. A*. 2007. **204**(5): 1423.
13. Barillaro G., Strambini L.M. An integrated CMOS sensing chip for NO_2 detection. *Sens. Actuators, B*. 2008. **134**(2): 585.
14. Ernst M., Brendel R., Ferre R. Thin macroporous silicon heterojunction solar cells. *Phys. Status Sol. RRL*. 2012. **6**(5): 187.
15. Ernst M., Brendel R. Macroporous silicon solar cells with an epitaxial emitter. *IEEE Journal of Photovoltaics.* 2013. **3**(2): 723.
16. Ernst M., Brendel R. Lambertian light trapping in thin crystalline macroporous Si layers. *Phys. Status. Sol. RRL*. 2014.**8**(3): 235.
17. Brendel R., Ernst M. Macroporous Si as an absorber for thin-film solar cells. *Phys. Status. Sol. RRL.* 2010. **4**(1–2): 40.
18. Maiolo J.R., Atwater H.A., Lewis N.S. Macroporous silicon as a model for silicon wire array solar cells. *J. Phys. Chem. C*. 2008. **112**(15): 6194.
19. Ernst M., Brendel R. Modeling effective carrier lifetimes of passivatedmacroporous silicon layers. *Sol. Energy Mater. Sol. Cells*. 2011. **95**(4): 1197.

Received 29.05.2017, accepted 20.06.2017