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Kinetics of Excess Carrier Distribution in Bilateral Macroporous Silicon with Different Thickness of Porous Layers

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The kinetics of the concentration distribution of excess minority charge carriers in bilateral macroporous silicon with different thicknesses of porous layers is presented. The dependence of the duration of the non-exponential beginning of relaxation of the distribution of the concentration of excess charge carriers in bilateral macroporous silicon on the thickness of the frontal macroporous layer is revealed. A similar dependence is observed in the rear macroporous layer 200 μm thick after the termination of the generation of excess charge carriers by light with a wavelength of 1.05 μm. The concentration of excess charge carriers in the frontal macroporous layer rapidly decreases due to the high generation and recombination of excess charge carriers. The decrease in the excess minority carrier concentration in the rear macroporous layer 100 μm thick and the monocrystalline substrate has a very short non-exponential part due to the low generation and recombination of excess minority charge carriers, respectively. The diffusion equation written for bilateral macroporous silicon is solved by a numerical method. The boundary and initial conditions are used for the solution. The boundary condition is written at the boundaries of macroporous layers. The initial distribution of the excess minority carrier concentration in bilateral macroporous silicon in the direction parallel to the pores is found from a system of equations. This initial distribution is calculated under the condition that macroporous silicon is illuminated with light with a wavelength of 0.95 μm or 1.05 μm. In the initial distribution of the excess minority carrier concentration, one or two maxima are observed. Two maxima are observed when bilateral macroporous silicon is illuminated with light at a wavelength of 0.95 μm.

Keywords: Macroporous silicon, Relaxation, Kinetics, Distribution of excess charge carriers.

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1. INTRODUCTION

Macroporous silicon is used in solar batteries [1]. The macroporous layer can be located on one or both sides of a solar cell. The rear side of the solar cell uses reflected light, which increases the efficiency of the solar cell. The solar energy efficiency management system monitors the consumption of electrical energy. The principles for constructing such a system for powering LED devices [2] have been developed, which makes it possible to efficiently use the electricity produced by a solar battery [3].

An increase in the absorption of electromagnetic radiation and photoconductivity is observed in two-dimensional macroporous silicon. The absorption spectra in macroporous silicon with microporous silicon layers on the pore surface contain oscillations [4]. These spectra were analyzed within the framework of the model of resonant scattering of electrons with infinite amplitude [5]. Photoconductivity in two-dimensional macroporous silicon depends on the angle of incidence of electromagnetic radiation. The increase in photoconductivity in macroporous silicon and its angular dependence are explained by the presence of macropores. Light penetrates the macropores and is additionally absorbed. The absorption of light depends on the angle of its incidence [6]. Instead of pores, single-crystal silicon nanowires can be etched. The light reflected from the nanowires is additionally absorbed, which increases the absorption and photoconductivity of silicon structured by nanowires. The reflection, absorption and transmission spectra of silicon structured by nanowires show a decrease in reflection and an increase in absorption due to surface structuring [7].

Using two transcendental equations, one can determine the effective lifetime of charge carriers in one- and bilateral macroporous silicon. These equations determine the effective lifetime of charge carriers in a silicon single crystal and in macroporous silicon with through pores, if the pore depth is equal to zero or the sample thickness [8]. The temperature of a macroporous silicon sample affects the effective relaxation time of photoconductivity in macroporous silicon [9]. The photoconductivity relaxation time sharply increases at temperatures from 190 to 280 K. Excess charge carriers in bilateral macroporous silicon have their own distribution. This distribution depends on the sample thickness, the thickness of the macroporous layers, the pore diameter, the thickness of the monocrystalline substrate, the bulk lifetime of minority charge carriers, the depth of light penetration into silicon, and the diffusion coefficient of charge carriers. Calculations of the concentration distribution of excess minority charge carriers show that the distribution has two maxima if the penetration depth of light into silicon is less than the sample thickness. Otherwise, one maximum is observed. Each of the maxima is observed near its illuminated surface. The calculations take into account that the light enters the bottom of the pores of frontal macroporous silicon [10].

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2. EXCESS CARRIER DISTRIBUTION KINETICS IN BILATERAL MACROPOROUS SILICON WITH DIFFERENT THICKNESSES OF POROUS LAYERS

Diffusion equation for excess minority charge carriers:

$$\frac{\partial \delta p(x,t)}{\partial t} = D_p \frac{\partial^2 \delta p(x,t)}{\partial x^2} - \frac{\delta p(x,t)}{\tau_b}, \qquad (2.1)$$

$\delta p(x,t)$ is the excess minority carrier concentration as a function of time, D_p is the diffusion coefficient of minority charge carriers, τ_b is the lifetime of excess minority charge carriers in the bulk of monocrystalline silicon substrate. Diffusion equation (2.1) should be supplemented with the initial and boundary conditions:

$$\delta p(x,0) = \delta p(x), \qquad (2.2)$$

$$g_s(x_0,t) - s_p \delta p(x_0,t) = e^{-1} j_p(x_0,t), \qquad (2.3)$$

where $\delta p(x)$, $\delta p(x,0)$, $\delta p(x_0,t)$ are the excess minority carrier concentrations in the equilibrium state, at the moment of onset of the nonequilibrium state and on the surface, respectively, $g_s(x_0,t)$ is the rate of surface generation excess charge carriers on the surface, e is the elementary charge, $j_p(x_0,t)$ is the current density of excess minority charge carriers on the surface, s_p is the surface recombination velocity of minority charge carriers on the surface.

The general solution of equation (1) is written as:

$$\delta p(t) = \sum_{n=1}^{\infty} A_n \exp\left(-\frac{t}{\tau_n}\right) \cos\left(n a_s x\right), \qquad (2.4)$$

where A_n are the Fourier series expansion coefficients depending on the initial distribution of excess minority charge carriers, τ_n are the relaxation time coefficients. There is a relationship between τ_n and a_s:

$$\frac{1}{\tau_n} = \frac{1}{\tau_b} + D_p a_s^2 n^2, \qquad (2.5)$$

where $\tau_{eff} = \tau_1$ is the effective relaxation time of excess minority charge carriers.

Consider a sample of bilateral macroporous silicon with thickness h. The thickness of a bilateral macroporous silicon wafer is much less than its length and width. Pores with depth h_1, h_2 are etched on two large planes of the plate. Macropores are etched perpendicular to the plane of the sample of bilateral macroporous silicon. Macropores and single-crystal silicon between macropores will be called a layer of macroporous silicon. Let a wafer of bilateral macroporous silicon be illuminated by light from the side of one layer of macroporous silicon. This layer of macroporous silicon will be called the frontal macroporous layer. The other macroporous layer will be called the rear macroporous layer. We choose the direction of the x-axis parallel to the direction of illumination (perpendicular to the plane of the sample). Boundary condition (2.3) written on the surfaces of a sample of bilateral macroporous silicon and a monocrystalline substrate:

$$\frac{dp_1}{dx}(0,t) = s_1 p_1(0,t), \qquad (2.6)$$

$$\frac{dp_3}{dx}(h,t) = s_2 p_3(h,t), \qquad (2.7)$$

$$\left(1-P_1\right) D_p \frac{dp_1}{dx}\left(h_1,t\right) = D_p \frac{dp_2}{dx}\left(h_1,t\right) - P_1 s_{por1} p_2\left(h_1,t\right), \qquad (2.8)$$

$$p_1\left(h_1,t\right) = p_2\left(h_1,t\right), \qquad (2.9)$$

$$\begin{aligned} &\left(1-P_2\right) D_p \frac{dp_3}{dx}\left(h-h_2,t\right) = \\ &= D_p \frac{dp_2}{dx}\left(h-h_2,t\right) - P_2 s_{por2} p_2\left(h-h_2,t\right), \end{aligned} \qquad (2.10)$$

$$p_2\left(h-h_2,t\right) = p_3\left(h-h_2,t\right), \qquad (2.11)$$

where $p_1(x,t)$, $p_3(x,t)$, $p_2(x,t)$ are the excess minority carrier concentrations in the frontal and rear macroporous layers and the monocrystalline substrate at time t, respectively, s_1, s_2, s_{por1}, s_{por2} are the surface recombination velocities of minority charge carriers on the sample surfaces and on the macropore surfaces of the frontal and rear macroporous layers, $P_1 = \pi(D_{por1}/2a_1)^2$, $P_2 = \pi(\mathrm{D}_{\mathrm{por2}}/2\mathrm{a}_2)^2$, D_{por1}, D_{por2}, a_1, a_2 are the volume fraction of pores, diameter, distance between the pores of the frontal and rear macroporous layer.

The initial concentration of excess minority charge carriers is found from the diffusion equation for excess minority charge carriers under stationary conditions:

$$D_p \frac{\partial^2 \delta p(x)}{\partial x^2} - \frac{\delta p(x)}{\tau_b} + g_{0p}(x)\exp(-\alpha x) = 0, \qquad (2.12)$$

where $\delta p(x)$ is the excess minority carrier concentration, α is the absorption coefficient of silicon, $g_0 p(\alpha)$ is the rate of generation of excess minority charge carriers on the illuminated surface.

The excess minority carrier concentration under stationary conditions in the frontal macroporous layer, the monocrystalline substrate, and the rear macroporous layer is written as:

$$\delta p_1(x) = C_1 \cosh\left(\frac{x}{L_1}\right) - C_2 \sinh\left(\frac{x}{L_1}\right) - \delta p_{g1}(x), \qquad (2.13)$$

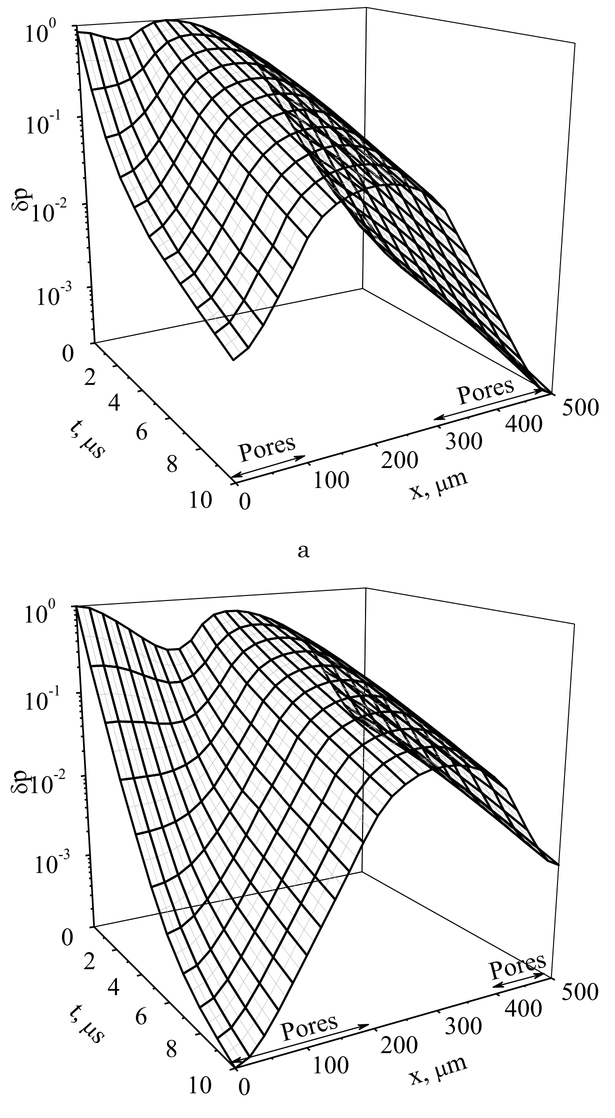
$$\delta p_2(x) = C_3 \cosh\left(\frac{x}{L_2}\right) - C_4 \sinh\left(\frac{x}{L_2}\right) - \delta p_{g2}(x), \qquad (2.14)$$

$$p_3(x) = C_5 \cosh\left(\frac{x}{L_3}\right) - C_6 \sinh\left(\frac{x}{L_3}\right) - \delta p_{g3}(x), \qquad (2.15)$$

where $\delta p_{g1}(x) = g_0 \alpha \tau_{eff1} \exp(-\alpha x)/((\alpha L_1)^2 - 1)$, $\delta p_{g2}(x) = g_0 \alpha \tau_\mathrm{b} ((1 - P_1)\exp(-\alpha x) + P_1 \exp(-\alpha x(x - h_1)))/((\alpha L_2)^2 - 1)$, $\delta p_{g3}(x) = g_0 \alpha \tau_3 ((1 - P_1)\exp(-\alpha x) + P_1 \exp(-\alpha x(x - h_1)))/((\alpha L_3)^2 - 1)$, $C_1 - C_6$ are constants, $L_1 = \sqrt{D_p \tau_{eff1}}$, $L_2 = \sqrt{D_p \tau_b}$, $L_3 = \sqrt{D_p \tau_{eff2}}$, τ_{eff1}, τ_{eff2} are the effective bulk lifetimes of minority charge carriers in the frontal and rear macroporous silicon. Constants C_1-C_6 are found from equations (2.6)-(2.11), (2.13)-(2.15).

3. RESULTS AND DISCUSSION

Fig. 1 shows the excess minority carrier concentration in bilateral macroporous silicon as a function of coordinate and time after the generation of excess charge carriers by light with a wavelength of 0.95 μm, incident on a macroporous layer with a thickness, μm: a) 100 μm, b) 200 μm. The excess minority carrier concentration was calculated for bilateral macroporous silicon with a thickness of 500 μm.



a

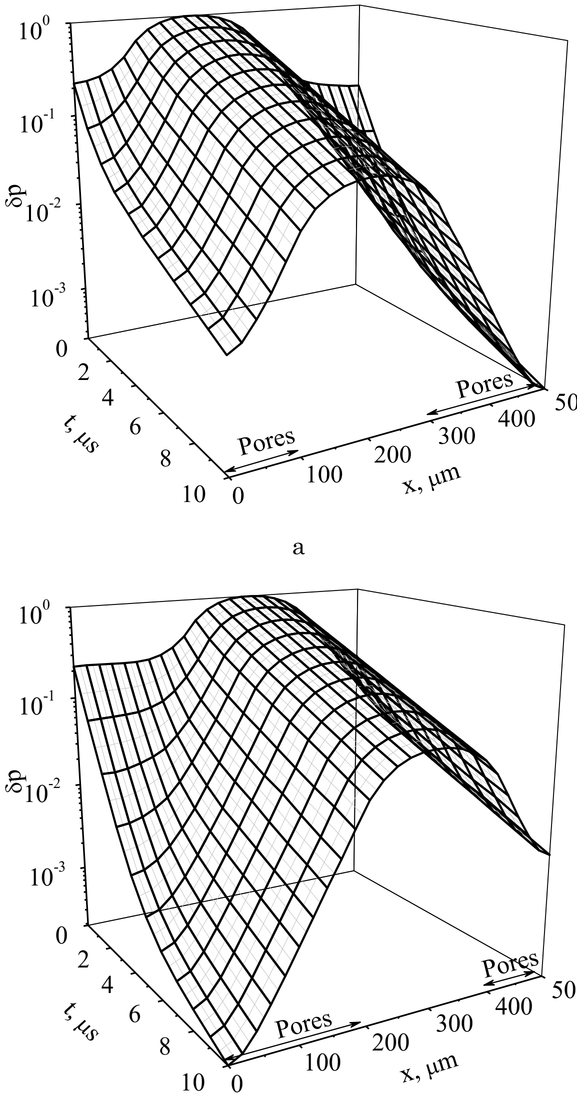
b

Fig. 1 – Concentration of excess minority charge carriers in bilateral macroporous silicon as a function of coordinate and time, after the termination of generation of excess charge carriers by light with a wavelength of 0.95 μm, incident on a macroporous layer with a thickness, μm: a) 100, b) 200

The bulk lifetime in a monocrystalline substrate is 10 μs. The depth of macropores of one of the layers of macroporous silicon is 100 μm and the other is 200 μm. The average diameter of macropores is 1 μm. The average distance between the pores is 2 μm. The surface recombination velocity on the surface of the pores and the sample is 1 m/s. Under stationary conditions, light propagates parallel to the pores and illuminates both the surface of porous silicon and the surface of the bottom of the pores, that is, the surface of a monocrystalline substrate. The initial distribution of the excess minority carrier concentration from the coordinate in bilateral macroporous silicon is calculated by formulas (2.6)-(2.11), (2.13)-(2.15). The remaining curves are calculated by the finite difference method from expression (2.1) with the initial condition and boundary conditions (2.6)-(2.11).

The initial dependence of the excess minority carrier concentration on the coordinate in bilateral macroporous silicon has two maxima if the excess charge carriers are generated by light with a wavelength of 0.95 μm. The maximum located near the surface of the macroporous silicon sample is less than the maximum located near the surface of the monocrystalline substrate if light is incident on a macroporous layer 100 μm thick and vice versa if light is incident on a macroporous layer 200 μm thick. Over time, the maximum in the monocrystalline substrate shifts from the surface to the middle of the monocrystalline substrate, and the maximum near the surface of the sample of bilateral macroporous silicon disappears. Fig. 1 shows that the dependence of the excess minority carrier concentration on the coordinate and time does not depend on which side a sample of bilateral macroporous silicon with different thicknesses of macroporous layers is illuminated already after 10 μs. The dependence of the excess minority carrier concentration on the coordinate decreases faster in the frontal macroporous layer with a pore depth of 200 μm than with a pore depth of 100 μm. Fig. 1 shows that the dependence of the excess minority carrier concentration on the coordinate and time in a monocrystalline substrate is almost the same. The decrease in the dependence of the concentration on the coordinate in the monocrystalline substrate and in the rear macroporous layer occurs according to an exponential law.

Fig. 2 shows the excess minority carrier concentration in bilateral macroporous silicon as a function of coordinate and time after the generation of excess charge carriers by light with a wavelength of 1.05 μm, incident on a macroporous layer with a thickness, μm: a) 100, b) 200. The initial dependence of the excess minority carrier concentration on the coordinate in bilateral macroporous silicon has one maximum if excess charge carriers are generated by light with a wavelength of 1.05 μm. The concentration maximum is located in the middle of the monocrystalline substrate. The position of the concentration maximum does not depend on which side of bilateral macroporous silicon with different thicknesses of the macroporous layers is illuminated. The decrease in the excess minority carrier concentration in the monocrystalline substrate and the rear macroporous layer with a thickness of 100 μm occurs according to an exponential law (see Fig. 1 and Fig. 2). In the rear macroporous layer 200 μm thick, the decrease in the concentration occurs according to a nonexponential law if excess charge carriers are generated by light with a wavelength of 1.05 μm. This is not observed in the rear macroporous layer in other cases (Fig. 1 and Fig. 2). Excess charge carriers in the macroporous layer quickly recombine due to recombination at



a

b

Fig. 2 – Concentration of excess minority charge carriers in bilateral macroporous silicon as a function of coordinate and time after the termination of generation of excess charge carriers by light with a wavelength of 1.05 μm, incident on a macroporous layer with a thickness, μm: a) 100, b) 200

the surface of the pores. Diffusion of charge carriers occurs from the monocrystalline substrate into the macroporous layer due to the concentration gradient of charge carriers; therefore, the farther from the monocrystalline substrate, the lower the excess minority carrier concentration. The greater the difference between the excess minority carrier concentration with and without sample illumination, the faster the concentration decreases, the longer the nonexponential part. The nonexponential part of the decrease in the excess minority carrier concentration is due to the sum of exponentials with constant coefficients in expression (4), which is the general solution of the diffusion equation.

4. CONCLUSIONS

The duration of the nonexponential beginning of relaxation of the concentration distribution of excess minority charge carriers in bilateral macroporous silicon depends on the thickness of the frontal macroporous layer. The excess minority carrier concentration decreases rapidly when there is high generation and recombination of excess minor charge carriers. In this case, the decrease in the concentration has a long nonexponential beginning. High generation and recombination of excess minority charge carriers is observed near the illuminated surface of the frontal macroporous layer. The decrease in the excess minority carrier concentration in the monocrystalline substrate and the rear macroporous layer with a thickness of 100 μm has a very short nonexponential part due to low recombination and generation of excess minority charge carriers, respectively. The decrease in the excess minority carrier concentration in the frontal macroporous layer with a thickness of 200 μm has a nonexponential part longer than 10 μs (time calculated by us) due to high generation and recombination of excess minority charge carriers. In the rear macroporous layer with a thickness of 200 μm, the decrease in the concentration has a long nonexponential part (more than 10 μs) if excess charge carriers are generated by light with a wavelength of 1.05 μm.

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Кінетика розподілу надлишкових носіїв заряду в двосторонньому макропористому кремнії з різною товщиною пористих шарів

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Представлена кінетика розподілу концентрації надлишкових неосновних носіїв заряду в двосторонньому макропористому кремнії з різною товщиною пористих шарів. Виявлена залежність тривалості не експонентного початку релаксації розподілу концентрації надлишкових носіїв заряду в двосторонньому макропористому кремнії від товщини фронтального макропористого шару. Аналогічна залежність спостерігається в тильному макропористому шарі товщиною 200 мкм після припинення генерації надлишкових носіїв заряду світлом з довжиною хвилі 1,05 мкм. Концентрація надлишкових носіїв заряду у фронтальному макропористому шарі спадає швидко завдяки високій генерації та рекомбінації надлишкових носіїв заряду. Зменшення концентрації надлишкових неосновних носіїв заряду в тильному макропористому шарі товщиною 100 мкм та монокристалічній підкладці має дуже коротку не експонентну частину завдяки низькій генерації та рекомбінації надлишкових неосновних носіїв заряду, відповідно. Рівняння дифузії, записане для двостороннього макропористого кремнію, розв'язано чисельним методом. Для розв'язку використовували граничну та початкову умови. Гранична умова була записана на межах макропористих шарів. Початковий розподіл концентрації надлишкових неосновних носіїв заряду в двосторонньому макропористому кремнії у напрямку, паралельному порам, знайдений з системи рівнянь. Цей початковий розподіл розраховувався за умови освітлення макропористого кремнію світлом з довжинами хвиль 0,95 мкм та 1,05 мкм. В початковому розподілі концентрації неосновних надлишкових носіїв заряду спостерігається один або два максимуми. Два максимуми спостерігаються при освітлені двостороннього макропористого кремнію світлом з довжиною хвилі 0,95 мкм.

Ключові слова: Макропористий кремній, Релаксація, Кінетика, Розподіл надлишкових носіїв заряду.