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Photoconductivity Kinetics in Bilateral Macroporous Silicon

V.F. Onyshchenko*

V.Ye. Lashkaryov Institute of Semiconductor Physics of National Academy of Sciences of Ukraine,
41, Nauky Ave., 03028 Kyiv, Ukraine

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The photoconductivity kinetics in bilateral macroporous silicon as a function of the pore depth of each macroporous layer is calculated by the finite-difference method. Steady-state photoconductivity in bilateral macroporous silicon is found using a system of equations. We use the excess minority carrier's diffusion equation, initial and boundary conditions to calculate the photoconductivity kinetics. Steady-state photoconductivity excited by light with a wavelength of 0.95 μm and 1.05 μm is used as the initial condition. We take into account that light passes through the frontal and rear macroporous layers, propagating through the silicon matrix and pores. The boundary condition is written at the boundaries of each macroporous layer. The kinetics of photoconductivity in bilateral macroporous silicon 500 μm thick is calculated under the condition that the pore depth of one macroporous layer is 100 μm, and the pore depth of another layer of macroporous silicon varies from 0 to 400 μm. It is shown that the initial photoconductivity decay period increases as the depth of each macroporous silicon layer increases. On a semi-logarithmic scale, the photoconductivity decay, which is described by an exponential law, changes its slope when the pore depth of the frontal or rear layer of macroporous silicon is more than 250 μm or 200 μm, respectively. The exponential part of the photoconductivity changes its slope no matter what wavelength of 0.95 μm or 1.05 μm excited stationary photoconductivity. The dependence of the photoconductivity kinetics on the pore depth of the frontal and rear layers of macroporous silicon is almost identical when the photoconductivity is excited by light with a wavelength of 1.05 μm. The photoconductivity decay in macroporous silicon with through pores is described by an exponential law.

Keywords: Macroporous silicon, Bilateral macroporous silicon, Photoconductivity kinetics.

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1. INTRODUCTION

Macroporous silicon and single-crystal silicon with a structured surface have found application in microelectronics and solar energy. The structure of the surface of macroporous silicon affects the reflection of light and determines its optical properties. The conditions for fabricating macroporous silicon using photoelectrochemical etching affect the surface structure and optical properties. Optimizing the fabrication of macroporous silicon significantly improves light capture by the macroporous surface and turns macroporous silicon into black silicon [1]. The optical properties of macroporous silicon and nanowires indicate a decrease in reflection and an increase in absorption of light. The decrease in light reflection is due to multiple reflections of light from the surfaces of nanowires. Light reflected from the surface of one nanowire hits the surface of another nanowire, and each time it partially passes through the surface [2]. The optical and electro-optical characteristics of textured solar cells are modelled using rigorous coupled-wave analysis and finite element method. Optical and electro-optical characteristics are calculated for different light trapping schemes [3]. The experimental absorption spectra of macroporous silicon structures with SiO_2 and CdS nanocoatings were analyzed in terms of the resonant electron scattering model [4]. The absorption spectra of two-dimensional photonic structures of macroporous silicon with microporous silicon layers on the pore surface contain oscillations in the infrared region. The oscillation period indicates the electro-optical Wannier-Stark effect [5]. Macroporous silicon is coated with a thin layer of Au/TiO_2 and Pt/TiO_2 photocatalyst. Such macroporous silicon photocatalytic structures have found application in the production of hydrogen from a water-ethanol mixture using ultraviolet light [6]. Macroporous silicon is used as a capacitor. The macroporous silicon capacitor is small in size and has a large specific capacitance and is suitable for system integration. Macroporous silicon is one of the electrodes. The surface of macroporous silicon is coated with an insulating layer of silicon oxide. The second electrode is a layer of nickel, which is electroplated over silicon oxide, on the surface of the pores [7]. In devices developed on the basis of macroporous silicon, it is important to know the concentration distribution of excess charge carriers. The distribution of excess carrier concentration in bilateral macroporous silicon is calculated depending on the pore depths of the macroporous layers. The calculation is made under the condition that excess charge carriers are generated by light with a wavelength of 0.95 or 1.05 μm. Cases are considered when the pore depth of one macroporous layer is equal or not equal to the pore depth of another macroporous layer [8]. In the distribution of excess carrier concentration, maxima are observed, which are located near the surface of the sample and the monocrystalline substrate (bottom of the pores). The maximum in a monocrystalline substrate is constantly observed. The maximum in the frontal macroporous layer is observed when bilateral macroporous silicon is illuminated with light that is strongly absorbed by silicon

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* onyshchenkovf@isp.kiev.ua

[9]. The distribution kinetics of the excess carrier concentration in bilateral macro-porous silicon is calculated depending on the thickness of porous layers. The high generation and recombination of excess charge carriers leads to the fact that the excess carrier concentration in the frontal layer of macroporous silicon rapidly decreases [10]. The photoconductivity relaxation time in macroporous silicon is found from two equations. One of the equations describes the diffusion of excess charge carriers in the macroporous silicon layer and their recombination on the pore surface and on the surface of the macroporous silicon layer. Another equation describes the diffusion and recombination of excess charge carriers in the monocrystalline substrate and on its surface, respectively. The photoconductivity relaxation time in macroporous silicon rapidly decreases if the pore depth increases from 0 to 25 μm [11].

2. PHOTOCONDUCTIVITY KINETICS IN BILATERAL MACROPOROUS SILICON

Let us consider a silicon single-crystal plate, which has pores etched on both sides perpendicular to the largest planes. A single crystal of silicon with etched pores on both sides is called bilateral macroporous silicon. Bilateral macroporous silicon has a thickness h. Steady-state photoconductivity is excited by light incident perpendicular to the surface of bilateral macroporous silicon. The kinetics of specific photoconductivity in bilateral macroporous silicon in the direction perpendicular to the pores is written as:

$$\begin{aligned}\delta\sigma(t) = \frac{e(\mu_n+\mu_p)}{h}\Bigg(&\frac{1-P_1}{1+P_1}\int_0^{h1}\delta p_1(x,t)dx + \\ +\int_{h1}^{h-h2}\delta p_m(x,t)dx + &\frac{1-P_2}{1+P_2}\int_{h-h2}^{h}\delta p_2(x,t)dx\Bigg),\end{aligned} \tag{2.1}$$

where t is the time, x is the coordinate, e is the electron charge, μ_n, μ_p are the mobilities of the majority and minority charge carriers, respectively, $\delta p_i(x, t)$ is the excess minority carrier concentration in the frontal ($i = 1$) and rear ($i = 2$) macroporous layers and monocrystalline silicon substrate ($i = m$), P_i and h_i are the pore volume fraction and pore depth of frontal ($i = 1$) and rear ($i = 2$) layers of macroporous silicon. The excess minority carrier concentration is found from the diffusion equation. The diffusion equation is written as:

$$\frac{\partial\delta p_i(x,t)}{\partial t} = D_p\frac{d^2\delta p_i(x,t)}{dx^2} - \frac{\delta p_i(x,t)}{\tau_i}, \tag{2.2}$$

where D_p is the diffusion coefficient of minority charge carriers, τ_i ($i = 1, 2, m$) is effective ($i = 1, 2$), bulk ($i = m$) lifetime of excess minority charge carriers in the frontal and rear macroporous layers and monocrystalline substrate, respectively. The diffusion equation for excess minority charge carriers (2.2) is written for the frontal and rear macroporous layer and monocrystalline substrate. The diffusion equation should be supplemented with the boundary condition, which is written at the boundaries of the sample and the monocrystalline substrate, and the initial condition. The initial and boundary conditions are written as:

$$\delta p_i(x,0) = \delta p_i(x),\ \ i = 1,\ 2,\ m, \tag{2.3}$$

$$D_p\frac{d\delta p_i}{dx}(x_i,t) = s_i\delta p_i(x_i,t), \tag{2.4}$$

$$\begin{aligned}&(1-P_i)D_p\frac{d\delta p_i}{dx}(x_{mi},t) = \\ &= D_p\frac{d\delta p_m}{dx}(x_{mi},t) - P_i s_{pori}\delta p_m(x_{mi},t),\end{aligned} \tag{2.5}$$

$$\delta p_i(x_{mi},t) = \delta p_m(x_{mi},t), \tag{2.6}$$

where $i = 1,\ 2,\ x_1 = 0,\ x_2 = h,\ x_{m1} = h,\ x_{m2} = h - h_2$, steady-state concentration of excess minority charge carriers in the frontal ($i = 1$) and rear ($i = 2$) macroporous layers and monocrystalline substrate ($i = m$) is found from the expression:

$$\delta p_i(x) = A_i\cosh\left(\frac{x}{L_i}\right) - B_i\sinh\left(\frac{x}{L_i}\right) - \delta p_{gi}(x), \tag{2.7}$$

A_i and B_i ($i = 1, 2, m$) are constants found from expressions (2.4)-(2.6), s_1, s_2, s_{por1}, s_{por2} are the surface recombination velocities on the surface of the sample and the pores of the frontal and rear macroporous layers, respectively, L_1, L_2, L_m are the diffusion lengths of minority charge carriers in the frontal and rear macroporous layers and monocrystalline substrate, respectively, $\delta pg_i(x) = g_0\alpha\tau_i exp(-\alpha x)K_i(x)/((\alpha L_i)^2 - 1)$, $K_1 = 1$, $K_2 = K_3$, $K_3 = 1 - P_1(1 - \exp(\alpha h_1))$, α is the coefficient of light absorption by silicon, g_0 is the excess carrier generation on the illuminated surface of bilateral macroporous silicon.

3. RESULTS AND DISCUSSION

Let us consider bilateral macroporous silicon 500 μm thick. Let light fall on one of the macroporous layers, let's call it the frontal macroporous layer, and let's call the other macroporous layer the rear macroporous layer. Light is incident on the monocrystalline substrate through the bottom of the pores. The kinetics of the photoconductivity in bilateral macroporous silicon was calculated under the condition that the pore depth of one macroporous layer is 100 μm and it does not change, while the pore depth of another layer of macroporous silicon varies from 0 to 400 μm. We calculate the kinetics of photoconductivity in bilateral macroporous silicon using expressions (2.1)-(2.7) and the following data: the minority carrier bulk lifetime in single-crystal silicon is 10 μs, the surface recombination velocity is 1.2 m/s, the macropore diameter is 2 μm, and the distance between them is 1 μm. The kinetics of specific photoconductivity in bilateral macroporous silicon $\delta\sigma$ is normalized to the steady-state specific photoconductivity of one-sided macroporous silicon of the same size $\delta\sigma m$, which has a macroporous layer from the rear (Fig. 1, Fig. 3, $h_1 = 0$, $h_2 = 100$ μm, $t = 0$) and frontal (Fig. 2, Fig. 4, $h_1 = 100$ μm, $h_2 = 0$, $t = 0$) sides. We will talk about the normalized photoconductivity because it is equal to the normalized specific photoconductivity.

The kinetics of the normalized photoconductivity in bilateral macroporous silicon 500 μm thick is presented depending on the pore depth of the frontal (Fig. 1) and rear (Fig. 2) macroporous layers. Steady state photoconductivity was excited by light with a wavelength of 0.95 μm. The pore depth of rear (Fig. 1) and frontal (Fig. 2) macroporous layers is 100 μm. Fig. 1 and Fig. 2 show the dependence of the kinetics of the normalized photoconductivity on the pore depth or the change in the dependence of the normalized photoconductivity on the pore depth over time in one-sided (Fig. 1 with $h_1 = 0$, $h_2 = 100$ μm, Fig. 2 with $h_1 = 100$ μm, $h_2 = 0$) and bilateral macroporous silicon and macroporous silicon with through pores (Fig. 1 with $h_1 = 400$ μm, $h_2 = 100$ μm and Fig. 2 with $h_1 = 100$ μm, $h_2 = 400$ μm).

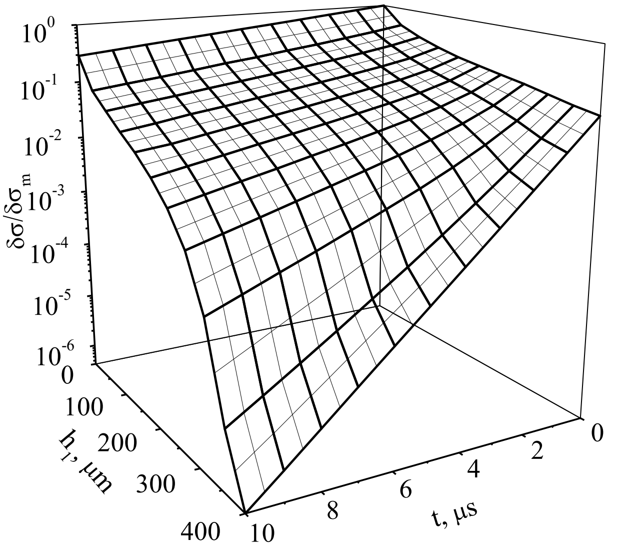

Fig. 1 – Kinetics of the normalized photoconductivity of bilateral macroporous silicon as a function of the pore depth of the frontal macroporous layer. Steady-state photoconductivity was excited by light with a wavelength of 0.95 μm. The pore depth of the rear macroporous layer is 100 μm

The kinetics of the normalized photoconductivity in macroporous silicon with through pores shown in Fig. 1 and Fig. 2 differs due to different normalization. The normalized steady-state photoconductivity ($t = 0$) sharply decreases when the pore depth of the frontal layer of macroporous silicon increases from 0 to 50 μm. The steady-state photoconductivity decreases almost exponentially when the pore depth increases from 50 to 400 μm (Fig. 1). The normalized steady-state photoconductivity ($t = 0$) slowly decreases as the pore depth of the macroporous silicon layer increases from 0 to 150 μm. The decrease in photoconductivity becomes noticeable when the pore depth increases from 150 to 400 μm (Fig. 2). The kinetics of photoconductivity is described by the sum of products with an exponent whose value depends on the characteristic time constant. The initial decay period of photoconductivity is not described by an exponential law as it is described by the sum of products with an exponent. The sum of products with an exponent decreases with time, and the kinetics of photoconductivity is described by an exponential law. The initial photoconductivity decay period increases when the pore depths of the frontal (Fig. 1) and rear (Fig. 2) layers of macroporous silicon increase. The normalized photoconductivity in macroporous silicon with through pores is described by an exponential law. In macroporous silicon with through pores, the recombination at the surface of the pores is much greater than the recombination at the surface of the sample of macroporous silicon. An exponential relationship on a semi-logarithmic scale is shown as a straight line. The exponential part of the normalized photoconductivity changes its slope when the pore depth of the frontal layer of macroporous silicon is greater than 250 μm (Fig. 1), or when the pore depth of the rear layer of macroporous silicon is greater than 200 μm (Fig. 2). The slope of the exponential part of the normalized photoconductivity changes due to an increase in the recombination of excess charge carriers. The recombination of excess charge carriers increases due to an increase in recombination on the surface of the pores of the frontal and rear macroporous layers. It increases due to the fact that the thickness of the monocrystalline substrate becomes less than two diffusion lengths of minority charge carriers and some of the excess charge carriers recombine not in the bulk of the monocrystalline substrate, but on the surface of macropores where recombination is greater.

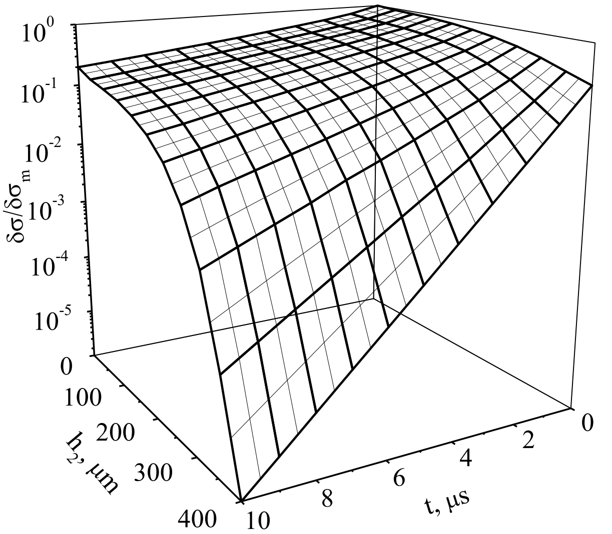

Fig. 2 – Kinetics of the normalized photoconductivity of bilateral macroporous silicon as a function of the pore depth of the rear macroporous layer. Steady-state photoconductivity was excited by light with a wavelength of 0.95 μm. The pore depth of the frontal macroporous layer is 100 μm

The kinetics of the normalized photoconductivity in bilateral macroporous silicon 500 μm thick is presented as a function of the pore depth of the frontal (Fig. 3) and rear (Fig. 4) macroporous layers. Steady-state photoconductivity was excited by light with a wavelength of 1.05 μm. The pore depth of the rear (Fig. 3) and frontal (Fig. 4) macroporous layers is 100 μm. The dependence of the kinetics of the normalized photoconductivity on the pore depth of the frontal (Fig. 3) and rear (Fig. 4) layers of macroporous silicon is almost identical. This is due to the initial uniformity of the excess carrier generation in bilateral macroporous silicon. The initial homogeneity of the excess carrier generation is due to the weak absorption of light with a wavelength of 1.05 μm by silicon. In this case, the light

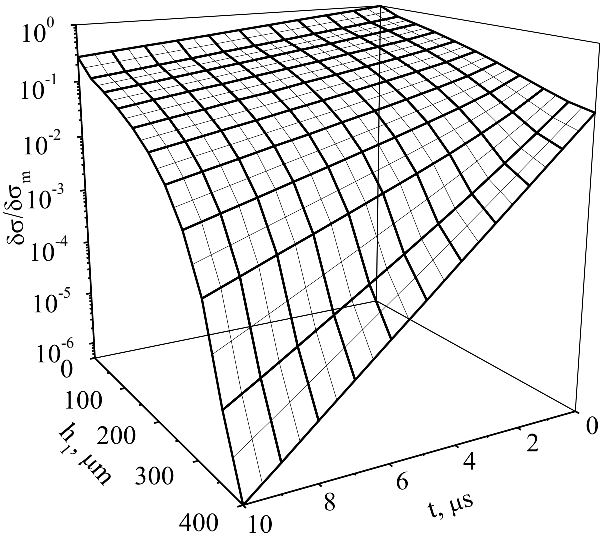

Fig. 3 – Kinetics of the normalized photoconductivity of bilateral macroporous silicon as a function of the pore depth of the frontal macroporous layer. Steady-state photoconductivity was excited by light with a wavelength of 1.05 μm. The pore depth of the rear macroporous layer is 100 μm

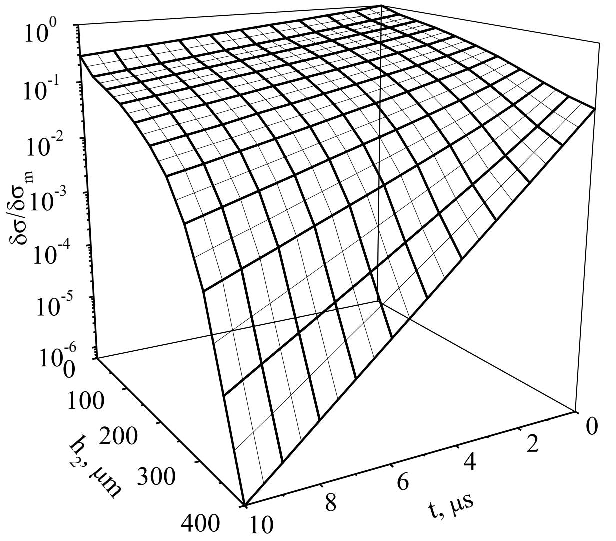

Fig. 4 – Kinetics of the normalized photoconductivity of bilateral macroporous silicon as a function of the pore depth of the rear macroporous layer. Steady-state photoconductivity was excited by light with a wavelength of 1.05 μm. The pore depth of the frontal macroporous layer is 100 μm

absorption law determines the stationary distribution of excess charge carriers in bilateral macroporous silicon. Diffusion of excess charge carriers is small because there are no large concentration gradients of excess charge carriers. The initial homogeneity of the excess carrier generation creates symmetry of the problem. This causes a similar photoconductivity kinetics in bilateral macroporous silicon with a change in the pore depth of the frontal or rear layer of macroporous silicon. The normalized photoconductivity in bilateral macroporous silicon slowly decreases with an increase in the pore depth of the rear or frontal layer of macroporous silicon from 0 to 200 μm. On a semi-logarithmic scale, the initial photoconductivity decay period increases, and the slope of the exponential part becomes steeper as the pore depths of the frontal or rear layer of macroporous silicon increase from 0 to 200 μm.

4. CONCLUSIONS

The initial photoconductivity decay period increases as the pore depth of the frontal or rear layer of macroporous silicon increases. An increase in the initial photoconductivity decay period is observed regardless of which wavelength of 0.95 μm or 1.05 μm excited steady-state photoconductivity. On a semi-logarithmic scale, the exponential part of the photoconductivity changes its slope when the pore depth of the macroporous silicon frontal layer is greater than 250 μm, or when the pore depth of the macroporous silicon rear layer is greater than 200 μm. The exponential part of the photoconductivity changes its slope regardless of which wavelength (0.95 μm or 1.05 μm) excited the steady-state photoconductivity. The slope of the exponential part of the normalized photoconductivity changes due to an increase in the recombination of excess charge carriers. The dependence of the photoconductivity kinetics on the pore depth of the frontal and rear layers of macroporous silicon is almost identical when the photoconductivity is excited by light with a wavelength of 1.05 μm. This is due to the initial homogeneity of the generation of excess charge carriers in bilateral macroporous silicon. The initial homogeneity of the generation of excess charge carriers is due to the weak absorption by silicon of light with a wavelength of 1.05 μm. Photoconductivity in macroporous silicon with through pores is described by an exponential law.

REFERENCES

1. G. Loget, A. Vacher, B. Fabre, F. Gouttefangeas, L. Joanny, V. Dorcet, *Mater. Chem. Frontier.* **1** No 9, 1881 (2017).
2. P.O. Gentsar, A.V. Stronski, L.A. Karachevtseva, V.F. Onyshchenko, *Phys. Chem. Solid State* **22** No 3, 453 (2021).
3. L.C. Andreani, A. Bozzola, P. Kowalczewski, M. Liscidini, *Sol. Energ. Mat. Sol. C.* **135**, 78 (2015).
4. L. Karachevtseva, S. Kuchmii, A. Stroyuk, O. Sapelnikova, O. Lytvynenko, O. Stronska, Wang Bo, M. Kartel, *Appl. Surf. Sci.* **338** Part A, 288 (2016).
5. L. Karachevtseva, Yu. Goltviansky, O. Sapelnikova, O. Lytvynenko, O. Stronska, Wang Bo, M. Kartel, *Appl. Surf. Sci.* **388** Part A, 120 (2016).
6. J. Serafin, L. Soler, D. Vega, A. Rodriguez, J. Llorca, *Chem. Eng. J.* **393** No1, 124701 (2020).
7. D. Vega, J. Reina, F. Martí, R. Pavon, A. Rodriguez, *Nanoscale Res. Lett.* **9** No 1, 473 (2014).
8. V.F. Onyshchenko, *Phys. Chem. Solid State* **23** No 1, 159 (2022).
9. V.F. Onyshchenko, *J. Nano – Electron. Phys.* **13** No 6, 06010 (2021).
10. V.F. Onyshchenko, *J. Nano - Electron. Phys.* **14** No 4, 04018 (2022).
11. V.F. Onyshchenko, L.A. Karachevtseva, M.I. Karas', *Emerging Sci. J.* **4** No 3, 192 (2020).

Кінетика фотопровідності в двосторонньому макропористому кремнії

В.Ф. Онищенко

Інститут фізики напівпровідників імені В.Є. Лашкарьова НАН України, пр. Науки, 41, 03028 Київ, Україна

Кінетика фотопровідності в двосторонньому макропористому кремнії в залежності від глибини пор кожного макропористого шару розрахована методом скінченних різниць. Стаціонарна фотопровідність в двосторонньому макропористому кремнії знайдена за допомогою системи рівнянь. Ми використали рівняння дифузії надлишкових неосновних носіїв заряду, початкову та граничну умови для розрахунку кінетики фотопровідності. Стаціонарна фотопровідність, яка збуджена світлом з довжинами хвиль 0,95 мкм та 1,05 мкм, використана як початкова умова. Ми врахували, що світло проходить через фронтальний та тильний макропористі шари розповсюджуючись по кремнієвій матриці та порам. Гранична умова записана на межах кожного макропористого шару. Кінетика фотопровідності в двосторонньому макропористому кремнії товщиною 500 мкм розрахована за умови, коли глибина пор одного макропористого шару дорівнює 100 мкм, а глибина пор іншого шару макропористого кремнію змінюється від 0 до 400 мкм. Показано, що початковий період затухання фотопровідності збільшується, коли глибина кожного шару макропористого кремнію збільшується. В напівлогарифмічному масштабі, спад фотопровідності, який описується експонентним законом, змінює свій нахил, коли глибина пор фронтального або тильного шару макропористого кремнію більше 250 мкм або 200 мкм, відповідно. Експонентна частина фотопровідності змінює свій нахил не залежно від того, якою довжиною хвилі 0,95 мкм чи 1,05 мкм збуджувалася стаціонарна фотопровідність. Залежність кінетики фотопровідності від глибини пор фронтального та тильного шарів макропористого кремнію є майже ідентичною, коли фотопровідність збуджується світлом з довжиною хвилі 1,05 мкм. Зменшення фотопровідності в макропористому кремнії з наскрізними порами описується експонентним законом.

Ключові слова: Макропористий кремній, Двосторонній макропористий кремній, Кінетика фотопровідності.