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*Vasyl Stefanyk Precarpathian
National University*

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V.F. Onyshchenko

Distribution of Excess Charge Carriers in Bilateral Macroporous Silicon with the Same Thickness of Porous Layers

V.Ye. Lashkaryov Institute of Semiconductor Physics of National Academy of Sciences of Ukraine, Kyiv, Ukraine,
onyshchenkovf@isp.kiev.ua

In this work, to calculate the distribution of the excess minority carrier concentration in bilateral macroporous silicon, the solution of the diffusion equation for stationary conditions is used, which is written for a monocrystalline substrate and macroporous layers. The solution to the diffusion equation is supplemented by boundary conditions at the interface between macroporous layers and a monocrystalline substrate and at the boundaries of a bilateral macroporous silicon sample. The dependence of the distribution of the excess minority carrier concentration in bilateral macroporous silicon with the same thickness of porous layers on the depth of macropores, the thickness of the sample of bilateral macroporous silicon, and the bulk lifetime of minority charge carriers is calculated. It is shown that the distribution function of the excess minority carrier concentration in bilateral macroporous silicon exhibits two maxima. The maxima are located in the frontal macroporous layer, near the surface of the sample, and in a monocrystalline substrate, near the interface, the frontal macroporous layer - monocrystalline substrate.

Keywords: bilateral macroporous silicon, porous silicon, excess charge carriers.

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Introduction

Macroporous silicon has found application in photosensors, photodetectors and solar cells [1]. A layer of macroporous silicon is located in a solar cell from one or both sides. Solar cells are characterized by their parameters. The parameters of high performance textured silicon solar cells are modelled to optimize them. Key parameters of textured silicon solar cells such as short circuit current, open circuit voltage and phototransformation efficiency are theoretically determined [2].The simulation takes into account such recombination mechanisms as non-radiative exciton recombination by the Auger mechanism with the participation of a deep recombinant level and recombination in the space charge region [3]. An analytical description of the photoconductivity relaxation model has shown that the photoconductivity relaxation time in macroporous silicon is determined from a system of two transcendental equations. The solution of this system showed that the relaxation of photoconductivity in a sample of macroporous silicon is limited by the diffusion of charge carriers from the monocrystalline substrate to the recombination surfaces in each macroporous layer [4]. This is evidenced by the mechanisms of charge carrier transfer through the surface barrier in macroporous silicon structures [5] and the temperature dependence of the photoconductivity kinetics measured in macroporous silicon at a temperature of 80 - 300 K [6]. The relaxation time of photoconductivity in macroporous silicon depends on the depth of macropores, which determines the size of the recombination surface in the pores. The relaxation time of photoconductivity rapidly decreases with increasing macropore depth from 0 to 25 µm due to the rapid growth of the recombination surface in the pores. The decrease in the relaxation time of photoconductivity slows down when the depth of macropores changes from 25 µm to 400 µm. At a macropore depth from 25 µm to 400 µm, the relaxation time of photoconductivity in macroporous silicon is determined by the diffusion of excess charge carriers [4].

A model is derived and applied, which determines the effective lifetime of minority carriers in samples of macroporous silicon depending on the bulk lifetime, surface passivation, and pore morphology [7]. The average pore diameter is 2.4 μm, the average distance between the pores is 5.2 μm. The calculations agree with the measurements at the surface generation velocity $S = 0.24$ m/s on the pore surface. The surface is passivized by thermal oxidation. The thickness of the silicon dioxide film is increased to improve surface passivation and reduce the effective lifetime of minority charge carriers [8]. The relationship between the morphology of the porous layer and the effective lifetime of minority charge carriers in one and bilateral macroporous silicon is modelled using an analytical model. The effective lifetime of minority carriers in bilateral macroporous silicon depends on such magnitudes as the bulk lifetime of minority carriers, the diffusion coefficient of minority carriers, and the thickness of the monocrystalline substrate. In addition, the effective lifetime depends on the values characteristic of each macroporous layer: the depth of macropores, the average diameter of macropores, the average distance between the centres of macropores, the volume fraction of macropores, and the surface generation velocity. Effective recombination of excess charge carriers in bilateral macroporous silicon is determined by the recombination of excess charge carriers on the surface of macropores and diffusion of charge carriers from the monocrystalline substrate to the recombination surfaces in each macroporous layer [9]. Transmission, reflection and absorption in porous structures show an increase in reflection and absorption due to light scattering in the porous layer [10].

The aim of this work is to apply a diffusion model with boundary conditions at the boundary of a monocrystalline substrate with porous layers and at the boundary of a sample to calculate and study the distribution of minority charge carriers in bilateral macroporous silicon.

I. Calculation method

Consider a bilateral macroporous silicon plate. Two sides of the macroporous silicon wafer have pores. Let one of these sides be illuminated with light. The origin of coordinates is chosen on the illuminated surface of the sample. Here x has a direction in the depth of the pores. The minority carrier diffusion equation for the one-dimensional case at steady state conditions is:

$$D_p\frac{\delta^2}{\delta x^2}\delta p(x)-\frac{\delta p(x)}{\tau_b}+g_0(x)\exp(-\alpha x)=0 \qquad (1)$$

Here D_p - diffusion coefficient of minority charge carriers, $\delta p(x)$ is the excess minority carrier concentration, α is the absorption coefficient of silicon, $g_{0p}(\alpha)$ is the generation velocity of excess minority charge carriers at the illuminated surface. Diffusion equations (1) must be supplemented with boundary conditions, which for stationary conditions is:

$$g_s(x_0)-s_p\delta p(x_0)=e^{-1}j_p(x_0), \qquad (2)$$

where e is the elementary charge, $\delta p(x_0)$ is the excess minority carrier concentration on the surface, $g_s(x_0)$ is the surface generation velocity of excess minority charge carriers on the surface, $j_p(x_0)$ is the current density of excess minority charge carriers at the surface, s_p is the surface generation velocity of minority charge carriers on the surface. The macroporous layer on which the light is incident will be called the frontal macroporous layer, and the other macroporous layer will be called the back layer.

The distribution of the excess minority carrier concentration under stationary conditions in the frontal macroporous layer in the x direction is written as:

$$\delta p_1(x)=C_1\cosh\left(\frac{x}{L_1}\right)-C_2\sinh\left(\frac{x}{L_1}\right)-\delta p_{g1}(\mathrm{x})\,, \qquad (3)$$

where C_1, C_2 are constants, $L_1=\sqrt{D_p\tau_1}$, τ_1 is the diffusion length and the effective bulk lifetime of minority charge carriers in the frontal macroporous layer, $\delta p_{g1}(x)=\frac{g_0\alpha\tau_1\exp(-\alpha x)}{(\alpha L^1)^2-1}$ is the surface generation velocity of excess minority charge carriers on the surface of the macroporous silicon sample (frontal macroporous layer). The concentration distribution of excess minority charge carriers under stationary conditions in a monocrystalline substrate is written as:

$$\delta p_2(x)=C_3\cosh\left(\frac{x}{L_2}\right)-C_4\sinh\left(\frac{x}{L_2}\right)-\delta p_{g2}(x), \qquad (4)$$

where C_2, C_3 are constants, $L_2=\sqrt{D_p\tau_2}$, τ_2 are the diffusion length and the effective bulk lifetime of minority charge carriers in a monocrystalline substrate, respectively, $\delta p_{g2}(x)=\frac{g_0\alpha\tau_2((1-P_1)\exp(-\alpha x)+P_1\exp(-\alpha(x-h_1)))}{(\alpha L_2)^2-1}$ is the surface generation velocity of excess minority charge carriers on the surface of the frontal macroporous silicon - monocrystalline substrate, $P_1=\pi D_{por1}{}^2/(4a_1{}^2)$ is the volume fraction of pores, h_1, D_{por1}, a_1 are the pore depth, pore diameter, and the distance between the pore centres of the frontal macroporous layer, respectively. This surface generation velocity takes into account the generation at the bottom of macropores of the frontal macroporous layer and light transmitted through the frontal macroporous layer. Note that the surface of the bottom of macropores of both layers will be referred to the surface of a monocrystalline substrate. The distribution of the excess minority carrier concentration under stationary conditions in a monocrystalline substrate and a back macroporous layer in the x direction is written as:

$$\delta p_3(x)=C_5\cosh\left(\frac{x}{L_3}\right)-C_6\sinh\left(\frac{x}{L_3}\right)-\delta p_{g3}(x), \qquad (5)$$

where C_5, C_6 are constants, $L_3=\sqrt{D_p\tau_3}$, τ_3 are the diffusion length and bulk lifetime of minority charge carriers in the back macroporous layer, respectively,

$\delta p_{g3}(x) = \frac{g_0 \alpha \tau_3 ((1-P_1)\exp(-\alpha x) + P_1 \exp(-\alpha(x-h_1)))}{(\alpha L_3)^2 - 1}$ is the surface generation velocity of excess minority charge carriers on the surface of monocrystalline substrate - back of macroporous silicon. We write the boundary conditions (2) in bilateral macroporous silicon in the form:

$$\frac{dp_1}{dx}(0) = s_1 p_1(0), \tag{6}$$

$$\frac{dp_2}{dx}(h) = s_2 p_2(h), \tag{7}$$

$$(1-P_1) D \frac{dp_1}{dx}(h_1) = D \frac{dp_2}{dx}(h_1) - P_1 s_{por1} p_2(h_1), \tag{8}$$

$$p_1(h_1) = p_2(h_2) \tag{9}$$

$$(1-P_2) D \frac{dp_3}{dx}(h-h_2) = \\ = D \frac{dp_2}{dx}(h-h_2) - P_2 s_{por2} p_2(h-h_2), \tag{10}$$

$$p_2(h-h_2) = p_3(h-h_2), \tag{11}$$

where s_1, s_2, s_{por1}, s_{por2} are the surface generation velocity of minority charge carriers on the front and rear surfaces of the sample and pores, respectively, $P_2 = \pi D_{por2}^2/(4a_2^2)$ is the volume fraction of pores, h_2, D_{por2}, a_2 is the pore depth, pore diameter and the distance between the centers of the pores of the back of the macroporous layer, respectively. The system of equations (6) - (11) has an exact solution, which can be found by one of the methods for solving the system of linear equations; it can also be solved numerically.

II. Distribution of excess charge carriers in bilateral macroporous silicon versus pore depth

Light is incident on the sample surface parallel to the pores. It illuminates the surface of macroporous silicon and the surface of the bottom of the pores, propagating through the pores. To calculate the distribution of the excess minority carrier concentration in bilateral macroporous silicon, the following parameters of macroporous silicon were used. The bulk lifetime of excess minority charge carriers in a monocrystalline silicon substrate was 10 µs. The thickness of the sample of macroporous silicon is 500 µm. The average diameter of macropores is 1 µm. The average distance between the centres of the pores is 2 µm. The effective bulk lifetime in both layers of macroporous silicon was 1 µs. The surface recombination velocity on the sample surface and on the pore surface of each macroporous layer was 1 m/s. The generation of excess charge carriers by light with a wavelength of 0.95 µm is inhomogeneous over the sample due to the fact that silicon strongly absorbs electromagnetic radiation of this wavelength. Light with a wavelength of 1.05 µm is weakly absorbed by silicon, therefore, the generation of excess charge carriers by this electromagnetic wave is uniform in a monocrystalline substrate and macroporous layers. Light creates an additional generation of excess charge carriers in the monocrystalline substrate and the back macroporous layer falling onto the surface of the bottom of the pores.

The distribution of the excess minority carrier concentration in bilateral macroporous silicon versus the pore depth when excess charge carriers are generated by light with a length of 0.95 µm and 1.05 µm is shown in Fig. 1 and Fig. 2.

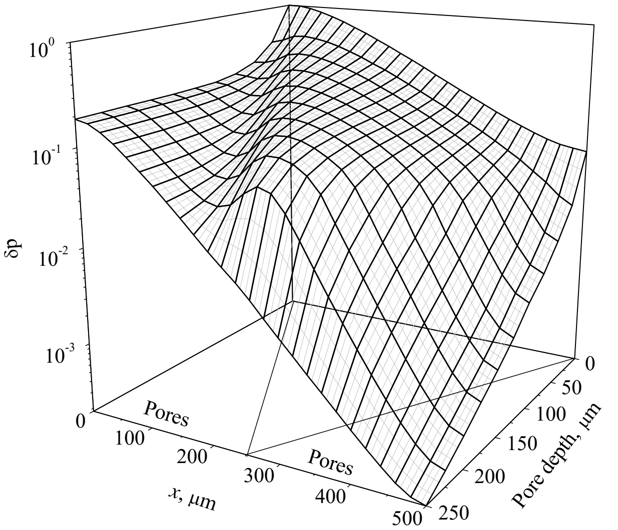

Fig. 1. Distribution of the excess minority carrier concentration in bilateral macroporous silicon depending on the pore depth, when light with a wavelength of 0.95 µm generates excess charge carriers.

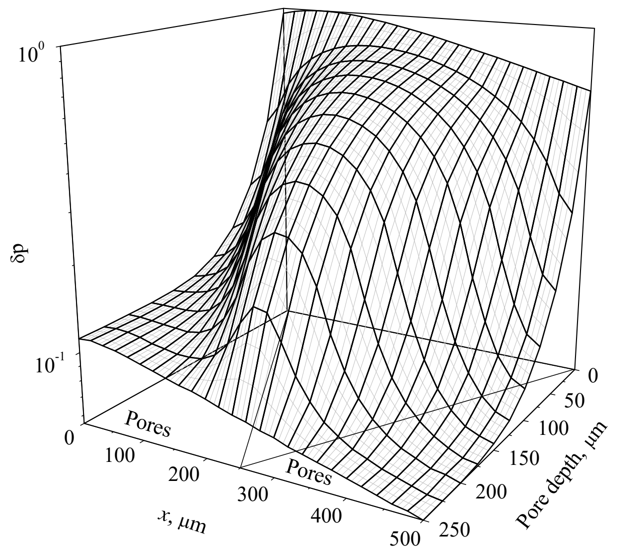

Fig. 2. Distribution of the excess minority carrier concentration in bilateral macroporous silicon depending on the pore depth, when light with a wavelength of 1.05 µm generates excess charge carriers.

The pore depth of the frontal macroporous layer is equal to the pore depth of the back macroporous layer. The pore depth of each layer varies from zero (no pores, that is, it is a silicon single crystal) to half the thickness of the sample of bilateral macroporous silicon, that is, the pores become through. When there are no pores, that is, in monocrystalline silicon, the distribution function of the concentration of excess minority charge carriers has a maximum, which is observed at the illuminated surface (see Fig. 1 and Fig. 2). Up to a pore depth of 100 μm, the maximum of the distribution function of the excess minority carrier concentration in double-sided macroporous silicon has one maximum, which is observed in a monocrystalline substrate at the interface between the frontal macroporous layer and a monocrystalline substrate.

In Fig. 1 shows that the excess minority carrier concentration on the frontal surface of the sample decreases with increasing pore depth to 100 μm, and then does not change. When the excess minority carrier concentration on the front surface of the sample ceases to change in the distribution function of the excess minority carrier concentration in bilateral macroporous silicon, two maxima appear (see Fig. 1). They are observed in the frontal macroporous layer, at the sample surface, and in a monocrystalline substrate, at the interface between the frontal macroporous layer and a monocrystalline substrate (see Fig. 1). Two peaks are due to: strong absorption of light with a wavelength of 0.95 μm by silicon, the presence of two surfaces on which electromagnetic radiation falls, and the diffusion of excess charge carriers.

When excess charge carriers are generated by light with a wavelength of 1.05 μm (see Fig. 2), the concentration distribution of excess minority charge carriers in bilateral macroporous silicon has one maximum, which is located in the middle of a monocrystalline substrate. As can be seen from Fig. 2, one maximum in the distribution function of the excess minority carrier concentration is observed for pore depths less than 200 μm. Two maxima are observed when the pore depth is more than 200 μm (see Fig. 2). Analysing the distribution of the excess minority carrier concentration in bilateral macroporous silicon under illumination with light with a wavelength of 0.95 μm and 1.05 μm, one can conclude that two maxima in the distribution function of the excess minority carrier concentration when the depth of light penetration into silicon is comparable with the pore depth of the frontal macroporous layer.

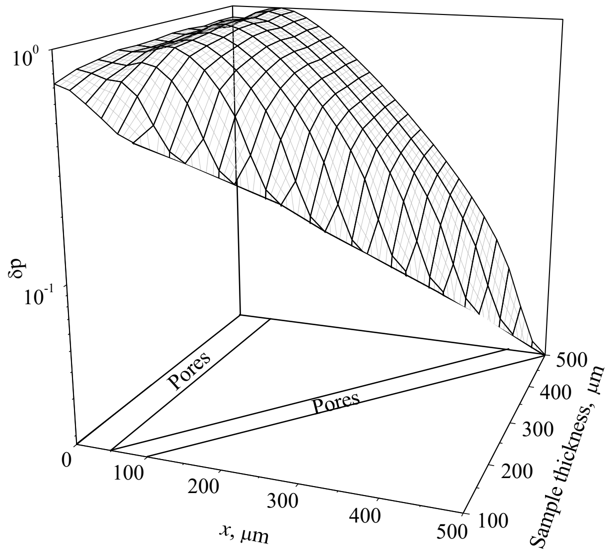

Fig. 3. Distribution of the excess minority carrier concentration in bilateral macroporous silicon depending on the sample thickness, when light with a wavelength of 0.95 μm generates excess charge carriers. The pore depth of each macroporous layer is 50 μm.

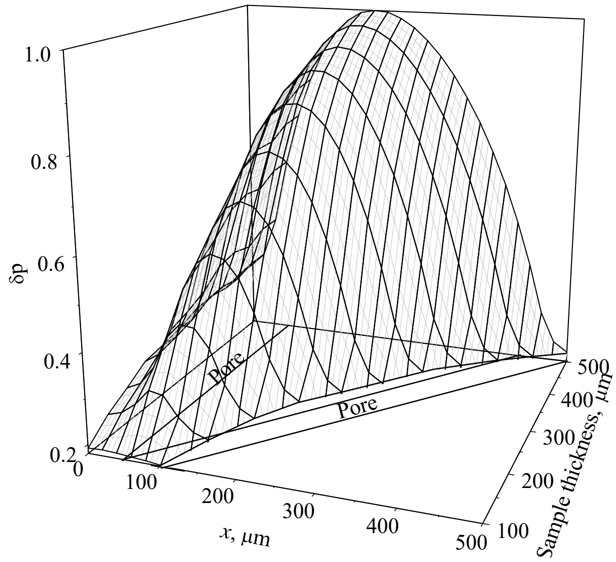

Fig. 4. Distribution of the excess minority carrier concentration in bilateral macroporous silicon depending on the sample thickness, when light with a wavelength of 1.05 μm generates excess charge carriers. The pore depth of each macroporous layer is 50 μm.

III. Distribution of excess charge carriers in bilateral macroporous silicon versus its thickness

The distribution of the excess minority carrier concentration in bilateral macroporous silicon versus the thickness of a sample of bilateral macroporous silicon, when excess charge carriers are generated by light with a wavelength of 0.95 μm and 1.05 μm, shown in Fig. 3 and Fig. 4, respectively. The pore depths of each macroporous layer were the same and equal to 50 μm. The thickness of the bilateral macroporous silicon sample varied from 100 μm to 500 μm. The pores were through when the sample thickness was 100 μm. The bulk lifetime in a monocrystalline silicon substrate was 10 μs.

The average diameter of macropores is 1 μm. The average distance between the centres of the pores is 2 μm. The effective bulk lifetime in both layers of macroporous silicon was 1 μs. The surface recombination velocity on the sample surface and on the pore surface of each macroporous layer was 0.1 m/s. As can be seen from Fig. 3, when a pore depth of 50 μm and excess charge carriers are generated by light with a wavelength of 0.95 μm, the distribution function of the excess minority carrier concentration in bilateral macroporous silicon has one maximum. The second maximum has not yet been observed due to the fact that the depth of light penetration into silicon is comparable to the pore depth. The depth of macropores in the sample is constant; therefore, the distribution of the concentration of excess minority charge carriers in each macroporous layer does not change. With a decrease in the thickness of the sample of bilateral macroporous silicon, the height of the maximum of the distribution function of the excess minority carrier concentration does not change (see Fig. 3).

As can be seen from Fig. 4, when a pore depth of 50 μm and excess charge carriers are generated by light with a wavelength of 1.05 μm, the distribution function of the excess minority carrier concentration in bilateral macroporous silicon has one maximum, which is located in the middle of a monocrystalline substrate. With a decrease in the thickness of a bilateral macroporous silicon sample from 500 μm to 100 μm, the height of the maximum of the distribution function of the excess minority carrier concentration decreases by a factor of 5 (see Fig. 4).

Conclusions

It is shown that the distribution function of the concentration of excess minority charge carriers in bilateral macroporous silicon exhibits two maxima. The maxima are located in the frontal macroporous layer, near the surface of the sample, and in the monocrystalline substrate, near the boundary of the frontal macroporous layer with the monocrystalline substrate.

Two maxima in the distribution function of the concentration of excess minority charge carriers are observed when the depth of light penetration into silicon is comparable to the pore depth of the frontal macroporous layer; in other cases, one maximum is observed. The maxima are observed when excess charge carriers are generated by light with a length of 0.95 μm and 1.05 μm.

Onyshchenko V.F. - PhD, Senior Research.

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В.Ф. Онищенко

Розподіл нерівноважних носіїв заряду в двосторонньому макропористому кремнії з однаковою товщиною пористих шарів

Інститут фізики напівпровідників імені В.Є. Лашкарьова НАН України, 03028, м. Київ, Україна,
onyshchenkovf@isp.kiev.ua

В роботі для розрахунку розподілу концентрації надлишкових неосновних носіїв заряду в двосторонньому макропористому кремнії використовується розв’язок рівняння дифузії для стаціонарних умов, який записується для монокристалічної підкладки та макропористих шарів. Розв’язок рівняння дифузії доповнюється граничними умови на межі макропористих шарів та монокристалічної підкладки та на межі зразка двостороннього макропористого кремнію. Розрахована залежність розподілу концентрації надлишкових неосновних носіїв заряду в двосторонньому макропористому кремнії з однаковою товщиною пористих шарів від глибини макропор, товщини зразка двосторонньому макропористому кремнії та об’ємного часу життя неосновних носіїв заряду. Показано, що в функції розподілу концентрації надлишкових неосновних носіїв заряду в двосторонньому макропористому кремнії спостерігаються два максимуми. Максимуми розташовані в фронтальному макропористому шарі, біля поверхні зразка, та в монокристалічній підкладці, біля межі фронтальний макропористий шар - монокристалічна підкладка.

Ключові слова: двосторонній макропористий кремній, пористий кремній, надлишкові носії заряду.