# Photoconductivity Relaxation Time in Macroporous Silicon

V. F. Onyshchenko [a*], L. A. Karachevtseva [b], M. I. Karas' [a]

[a] Senior Researcher,V. Lashkaryov Institute of Semiconductor Physics, NAS of Ukraine, Kyiv-28, Ukraine

[b] Head of laboratory, V. Lashkaryov Institute of Semiconductor Physics, NAS of Ukraine, Kyiv-28, Ukraine

## Abstract

Macroporous silicon has found applications in sensors, receivers, integrated microchips and solar cells. In this work, we first showed analytically the photoconductivity relaxation time of in macroporous silicon is determined from a system of two transcendental equations. The analytical description of the photoconductivity relaxation model contains the diffusion equation solution both in single crystal substrate and in an effective medium of macroporous layer, as well as boundary conditions recorded for the surfaces of the layer of macroporous silicon and single crystal substrate. We showed that the photoconductivity relaxation time in macroporous silicon rapidly decreases with increasing macropore depth from 0 to 25 μm and reduced thicknesses of the single crystal substrate from 250 to 0 μm. The photoconductivity recombination time in the sample of macroporous silicon is limited by the diffusion of charge carriers from the substrate to the recombination surfaces in the macroporous layer. The system of transcendental equations that we have found will find application in calculating the relaxation time of photoconductivity in macroporous silicon devices such as sensors, receivers, and solar cells.

## 1- Introduction

Macroporous silicon is used in microelectronics, optics and optoelectronics due to its simplicity of manufacture, structural and physical properties, and the possibility of integration into microcircuits. A layer of macroporous silicon improves the absorption of light; therefore it has found application in solar cells [1, 2]. Macropores are created by photoelectrochemical etching on a single-crystal silicon wafer from which a solar cell will be made. The analytical model calculates the relationship between the morphology of the macroporous layer and light absorption and optimizes the opto-electrical parameters of a solar cell that has a layer of macroporous silicon [3]. Theoretical model calculates the efficiency of a textured silicon solar cell depending on its thickness [4]. She considers two mechanisms that determine the optimal thickness of a solar cell. The first mechanism is associated with an increase in the mean free path of photons in a solar cell made of textured silicon. The second mechanism is due to surface recombination on the front surface [5]. The analysis of the photoelectric conversion efficiency of high-performance silicon solar cells with n-type and p-type bases is performed for the case when the Shockley-Reed-Hall recombination in the bulk of silicon is determined by a deep level. The photoelectric conversion efficiency increases in solar cells with an n-type base and decreases in solar cells with a p-type base with increasing doping due to asymmetry of recombination parameters [5]. A layer of macroporous and porous silicon is used as a broadband antireflection coating for solar cells [6]. Coating the surface of porous silicon with a thin carbon film made it possible to significantly increase the efficiency and stability of the electron emission current. The experimental results were explained by the presence of a dipole layer of Si-H and oxide on the silicon surface [7]. The surface of macroporous silicon is oxidized to reduce recombination on the surface and increase the lifetime of excess charge carriers [8]. The dependence of the effective lifetime of minority charge carriers and in black silicon structured by cones and pyramids is calculated on the diameter of the base of the cone,

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side of the base of the pyramid, the height of the cone and pyramid [9]. The depth of the macropores, the diameter of the macropores, the distances between the macropores and the surface recombination rate affect the specific photoconductivity of macroporous silicon [10, 11]. The diffuse model of photoconductivity relaxation and the mechanisms of electron transport in macroporous silicon are presented in Karachevtseva et al. (2017) [12] study. The mechanisms of charge carrier transport through the surface barrier in the electroluminescent structures of porous silicon are shown in Evtukh et al. (2006) [13] study. The photoconductivity relaxation time in macroporous silicon is calculated by the finite difference method. The distribution of excess minority carriers in the macroporous silicon is calculated by the finite difference method for calculating the photoconductivity in the macroporous silicon [14]. The effective lifetime of minority charge carriers in macroporous silicon with a macroporous layer on each side is determined from a system of two transcendental equations. The system of equations was found by solving the diffusion equation written for each macroporous layer and single-crystal substrate. The solution of the diffusion equation is supplemented by the boundary conditions on the surfaces of the sample and on the boundary between each macroporous layer and a single crystal substrate [15]. Macroporous silicon is used in gas-sensitive devices and IR optical filters [16, 17]. An electrochemical sensor made of macroporous silicon has found application for the detection of hydrogen peroxide. The macroporous silicon layer in the sensor had an average thickness of 80 μm and an average pore diameter of 4 to 6 μm. The sensor shows a linear characteristic in a wide range of concentrations of the substance [18]. Selective thermal emitters made of macroporous silicon photonic crystals are used to detect carbon dioxide [19]. Absorption in macroporous silicon and macroporous silicon photonic crystals is due to absorption on free carriers and Lambertian light trapping. Numerical modeling showed that Lambertian light trapping is the predominant absorption mechanism in the band gap region [20].

The aim of this work is to find the photoconductivity relaxation time in macroporous silicon, which is determined by a system of two transcendental equations. We must determine the relationship between the relaxation time of photoconductivity in macroporous silicon and the depth of the macropores, the size of the macropores, the distance between the macropores, thickness of macroporous silicon, and the surface recombination rate.

## 2- The Photoconductivity Relaxation Time in Macroporous Silicon

Consider n-type silicon. The distribution of excess minority charge carriers is described by the diffusion equation. In the general case, the minority carrier diffusion equation is:

$$\frac{\partial}{\partial t}\delta p(t) = D_p \frac{\partial^2}{\partial x^2}\delta p(t) - \frac{\delta p(t)}{\tau_b} + g_p(t) \tag{1}$$

Where t is time, $\delta p(t)$ is the excess hole concentration, $D_p$ is the diffusion coefficient of holes, x is the coordinate, $\tau_b$ is the bulk minority carrier lifetime in silicon single crystal, $G_p(t)$ is the excess hole generation rate. In our case, carrier generation switched off at t=0 $G_p(t=0)=0$. Boundary conditions:

$$g_s(x_s, t) - s_p\delta p(x_s, t) = e^{-1}j_p(x_s, t) \tag{2}$$

Where $g_s(x_s,t)$ is the surface generation rate of holes, $s_p$ is the surface recombination rate of holes, $\delta p(x_s,t)$ is the excess hole concentration at the surface, e is the elementary charge, $j_p(x_s,t)$ is the current density of excess hole at the surface. The general solution of Equation 1 is:

$$\delta p(x, t) = \sum_{n=1}^{\infty} A_n \exp\left(\frac{t}{\tau_n}\right)\cos(na_s x) \tag{3}$$

Where $A_n$ is the Fourier series expansion coefficients for the initial distribution of excess holes, $\tau_n$ are characteristic time constants, n are natural numbers, $a_s$ is a constant characteristic number. Between $\tau_n$ and $a_s$ there is a relationship:

$$\frac{1}{\tau_n} = \frac{1}{\tau_b} + D_p a_s^2 n^2 \tag{4}$$

### 2-1- Schematic Cross Section of Macroporous Silicon

Figure 1 schematically shows a section of macroporous silicon. The light was incident on the macroporous layer parallel to the macropores. He illuminated a single-crystal substrate along the bottom of macropores and silicon between pores. Under such conditions, the distribution function of excess holes will have a maximum in the single-crystal substrate. The origin of the x axis is chosen at the maximum point. The x axis is directed parallel to the pores, towards the macropores. The bottom of the macropores has the coordinate $h_1$, the surface of the single-crystal substrate has the coordinate - $h_0$ as shown in Figure 1. The diffusion of charge carriers from the single-crystal substrate to the macroporous layer begins after switch off the light. This is equivalent to the fact that surface generation of excess charge carriers from the plane passing through the bottom of the macropores to the macroporous layer will occur.
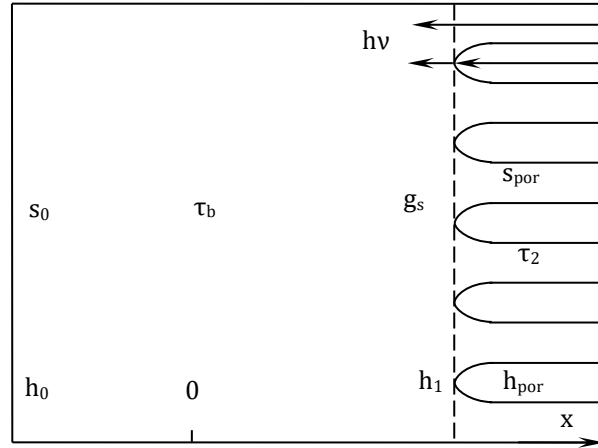
**Figure 1. Schematic cross section of macroporous silicon.**

### 2-2- Boundary Conditions Recorded for the Layer of Macroporous Silicon

If the thickness of the macroporous layer $h_{por}$ is much larger than the diffusion length in the macroporous layer $L_2$ $h_{por} \gg L_2$, the boundary conditions for the layer of macroporous silicon are written as follows:

$$x = h_1; g_s(h_1, t) - s_p \, \delta p_2(h_1, t) = D_p \frac{dp_2}{dx}(h_1, t) \tag{5}$$

$$x \to \infty; \ \delta p_2(x, t) \to 0 \tag{6}$$

### 2-3- The General Solution of Diffusion Equation Recorded for the Layer of Macroporous Silicon and the Single-crystal Substrate

The general solution of the minority carrier diffusion equation recorded for a layer of macroporous silicon, with the second boundary condition (6), can be rewritten as follows:

$$\delta p_2(x, t) = \delta p_2(h_1, t) \exp\left(-\frac{x}{L_2}\right) \tag{7}$$

From the first boundary condition (5) we find $\delta p_2(h_1,t)$. If we substitute $\delta p_2(h_1,t)$ in expression (7), then the distribution function of excess charge carriers in the macroporous silicon layer can be written as follows:

$$\delta p_2(x, t) = \frac{L_2 g_s(h_1, t)}{D_p} \exp\left(-\frac{x}{L_2}\right) \tag{8}$$

Where $s_p = 0$. If $t \gg \tau_1$, then from expression (3) the distribution function of excess charge carriers in the single-crystal substrate $\delta p_1(x,t)$ is:

$$\delta p_1(x, t) = A_1 \exp\left(\frac{t}{\tau_1}\right) \cos(a_s x) \tag{9}$$

### 2-4- Boundary Condition at the Surface of Single-crystal Substrate

The boundary condition (2) at the surface of the single-crystal substrate $h_1$ is written as follows.

$$j_{1p}(h_1, t) = (1 - P)g_s(h_1, t) + P s_{por}\delta p_1(h_1, t) \tag{10}$$

where $j_{1p}(h_1,t)$ is diffusion hole current density at the surface of the single-crystal substrate $h_1$, $g_s(h_1,t)$ is the surface generation rate of holes of holes at the plane $h_1$, P is the pore volume fraction, $s_{por}$ is the surface recombination rate of holes at the surface of the pore. From the definition of the diffusion hole current density at the surface of the single-crystal substrate $h_1$ and expression (9) we have:

$$j_{1p}(h_1, t) = -D_p \frac{\partial}{\partial x}\delta p_1(h_1, t) = D_p \delta p_1(h_1, t) a_s \tan(a_s h_1) \tag{11}$$

### 2-5- Boundary Condition at the Surface of Macroporous Layer – monocrystalline Substrate

The boundary condition (2) at the surface of the macroporous layer $h_1$ is:

$$g_s(h_1, t) = j_{2p}(h_1, t) = -D_p \frac{\partial}{\partial x}\delta p_2(h_1, t) = \frac{D_p}{L_2}\delta p_2(h_1, t) \tag{12}$$

We did not take into account the recombination at the bottom of the macropores that the bottom of the macropores belongs to the surface of a single crystal substrate. From the expressions (10 –12) we have:

$$-\frac{D_p(1-P)}{L_2}\delta p_2(h_1,t) - Ps_{por}\delta p_1(h_1,t) = -D_p\delta p_1(h_1,t)a_s\tan(a_sh_1) \tag{13}$$

Due to the fact that the condition $p_1(h_1,t) = p_2(h_1,t)$ is satisfied at the surface $h_1$, the expression (13) is rewritten as:

$$a_s\tan(a_sh_1) = \frac{1-P}{L_2} + \frac{Ps_{por}}{D_p} \tag{14}$$

We can rewrite expression (14) as:

$$a_s\tan(a_sh_1) = \frac{1}{D_p}\left(\frac{D_p(1-P)}{L_2} + Ps_{por}\right) = \frac{s_2}{D_p} \tag{15}$$

According to expression (15), we write the surface recombination rate at the surface $h_1$ as follows:

$$s_2 = \frac{D_p(1-P)k}{L_2} + Ps_{por} \tag{16}$$

Here we wrote the coefficient k, which is related to the fact that the macroporous layer has a finite size.

### 2-6- Analytically Construct the Dependence of k on the Depth of Macropores

Figure 2 shows the dependence of the surface recombination rate on the depth of the macropores at the surface $h_1$. The dependence of k on the depth of macropores was selected analytically. For the calculation, the surface recombination rate on the surface of macropores $s_{por}=100$ m/s was used. The stationary distribution of the excess minority carrier concentration was calculated for macroporous silicon with a thickness of h=500 μm. The depth of the macropores is $h_{por}=100$ μm, the diameter of the macropores is $D_{por}=2$ μm, and the distance between the centers of the macropores is $a=4$ μm. The surface recombination rate on the surface of a macroporous silicon sample is $s_1 = 100$ m/s.
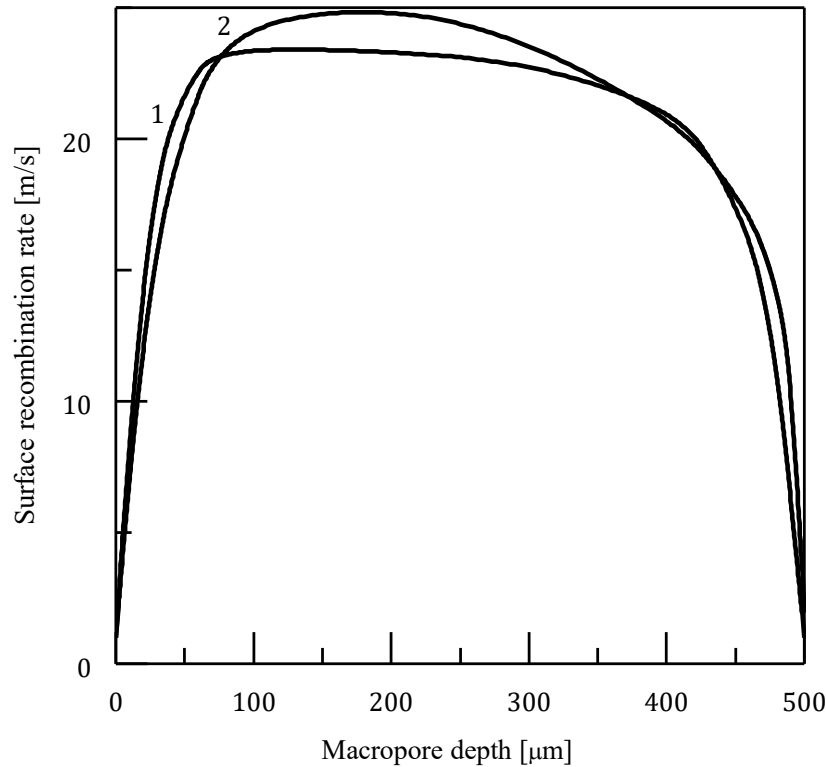


Figure 2. The surface recombination rate on the surface $h_1$, calculated by expression (16) - 1, and by expression (18) - 2.

The stationary distribution of the excess minority carrier concentration in macroporous silicon δp(x), when illuminated through macropores, was found in Karachevtseva et al. (2017) [12] study. Stationary boundary condition at the surface $h_1$ is written as follows:

$$s_p \delta p(h_1) = D_p \frac{d\delta p}{dx}(h_1) \tag{17}$$

From expression (17) we find the surface recombination rate at the surface $h_1$:

$$s_2 = \frac{D_p}{\delta p(h_1)} \frac{d\delta p}{dx}(h_1) \tag{18}$$

That is, if we know the stationary distribution of the excess minority carrier concentration in macroporous silicon, then we can find the surface recombination rate at the surface $h_1$.

As shown in Figure 2, the dependence of the surface recombination rate on the depth of macropores increases to 25 m/s if the depth of the macropores increases from 0 to 100 μm, and decreases almost symmetrically when the depth of the macropores varies from 400 μm to 500 μm. The surface recombination rate decreases very slowly when the depth of the macropores increases from 100 μm to 400 μm. A rapid increase in the surface recombination rate is modeled by an exponential function in which the argument is the double depth of macropores normalized to the effective diffusion length in the macroporous silicon layer $2h_{por}/L_2$. A rapid decrease in the surface recombination rate is modeled by an exponential function in which the argument is the double thickness of the single crystal substrate normalized to the effective diffusion length in the macroporous silicon layer $2(h-h_{por})/L_2$. We selected the coefficient k by comparing the surface recombination rates calculated by expressions (16) and (18), as shown in Figure 2.

### 2-7- The System of Equations Determines the Photoconductivity Relaxation Time in Macroporous Silicon

Expression (15) with an analytically selected coefficient k was written as follows:

$$a_s \tan(a_s h_1) = \frac{1}{D_p}\left(\frac{D_p(1-P)k}{L_2} + Ps_{por}\right) \tag{19}$$

Where

$$k = \left(\frac{2}{\exp\left(-\frac{2h_{por}}{L_2}\right)\left(\frac{2}{s_0 L_2 D_p^{-1} + 1} - 1\right) + 1} - 1\right) \times \left(\frac{2}{\exp\left(-\frac{2(h - h_{por})}{L_2}\right)\left(\frac{2}{s_0 L_2 D_p^{-1} + 1} - 1\right) + 1} - 1\right) \tag{20}$$

The effective diffusion length $L_2=(D_p\tau_2)^{1/2}$ in the macroporous silicon layer can be found using the formula for the effective minority carrier lifetime in macroporous silicon layer [12]:

$$\frac{1}{\tau_2} = \frac{1}{\tau_b} + \frac{\pi D_{por} s_{por}}{a^2 - 0.25\pi D_{por}^2} \tag{21}$$

We write the boundary condition on the surface of a single-crystal substrate $h_0$:

$$a_s \tan(a_s h_0) = \frac{s_1}{D_p} \tag{22}$$

From expression (4), we write the relaxation time of photoconductivity in macroporous silicon as:

$$\frac{1}{\tau_1} = \frac{1}{\tau_b} + D_p a_s^2 \tag{23}$$

The system of Equations 19, 22 and 23 determines the relaxation time of photoconductivity in macroporous silicon.

## 3- Results and Discussions

We used a numerical method to verify the accuracy of calculations performed using a system of analytical equations, which determines the effective lifetime of minority charge carriers in macroporous silicon. For the calculation, the bulk minority carrier lifetime in silicon single crystal is 10 μm, the surface recombination rate is 100 m/s, the diameter of the macropores was 2 μm, and the distance between the centers of the macropores is 4 μm. The effective lifetime of minority charge carriers in a layer of macroporous silicon calculated by Equation 21 is 1 μm.

### 3-1- Comparison with Numerical Calculation

Figure 3 shows the dependence of the photoconductivity relaxation time in macroporous silicon on porous layer thickness. The dependence is calculated from the system of Equations 19, 22, 23 and is shown by a solid curve. We

also calculated by the numerical method the photoconductivity relaxation time depending on the depth of macropores [12], shown by filled circles in Figure 3. Photoconductivity relaxation time in macroporous silicon decreases rapidly if the depth of the macropores increases from 0 to 25 μm (see Figure 3). This rapid decrease in relaxation time is due to the fact that the area of recombination surfaces in the macroporous silicon layer increases with increasing the depth of the macropores. The recombination of excess charge carriers increases with an increase in the area of macropores. Figure 3 shows photoconductivity relaxation time slowly decreases if the depth of the macropores grows from 25 to 250 μm. This slow decrease in the relaxation time is due to the limitation of recombination at surfaces by diffusion of excess charge carriers to the recombination surface. Excess charge carriers that are generated directly in the macroporous layer and those charge carriers that diffuse from the single crystal substrate recombine on the surface of the macropores. Recombination cannot grow more than a certain value, because it will be limited by the diffusion of excess charge carriers to recombination surfaces. Excess charge carriers will not have time to diffuse to the recombination surfaces. Thus, the surface recombination rate in the macroporous layer will be limited by diffusion, no matter how large it is. Under such conditions, surface recombination is determined not by the surface recombination rate, but by the diffusion time of charge carriers to recombination surfaces, which depends on the diffusion coefficient. Figure 3 shows that photoconductivity relaxation time decreases rapidly if the depth of the macropores increases from 250 to 500 μm. This rapid decrease in relaxation time is explained by a decrease in the effect of diffusion on recombination processes. The diffusion of excess charge carriers limits their recombination at the surface until the thickness of the single crystal substrate becomes much less than two diffusion lengths. When the thickness of the single-crystal substrate decreases, then the diffusion time of excess charge carriers to the recombination surface becomes shorter. Diffusion ceases to limit the recombination of charge carriers at the surface at small distances, and causes a rapid decrease in the relaxation time.
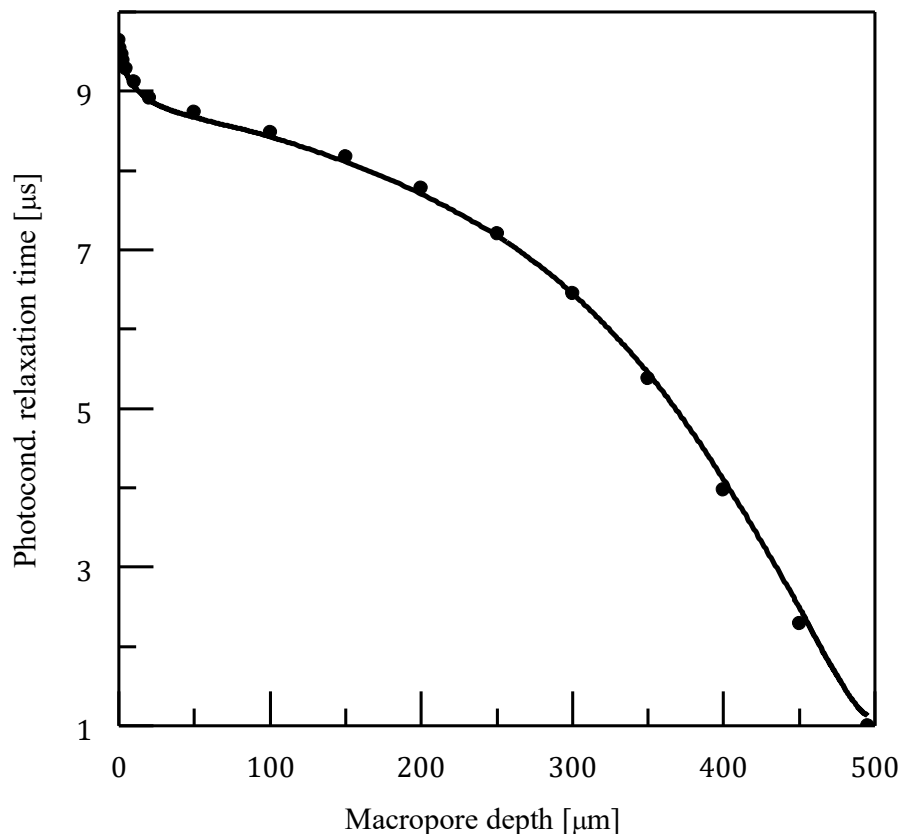


**Figure 3. The dependence of photoconductivity relaxation time in macroporous silicon on the depth of the macropores is shown as a solid line. Circles show numerical calculations of photoconductivity relaxation time [12].**

### 3-2- The Calculation of Photoconductivity Relaxation Time Depending on the Depth of Macropores, the Bulk Lifetime, and Thickness of Macroporous Silicon

Figures 4 to 9 shows the dependence of the relative relaxation time of photoconductivity on the thickness of the porous layer and the bulk lifetime at different thickness of macroporous silicon. The dependence of the effective relaxation time of photoconductivity is presented on a semi-logarithmic scale. The dependence is calculated from the system of Equations 19, 22, 23. The parameters of macroporous silicon, which were used to calculate the relative relaxation time of photoconductivity, were indicated above.

A series of white curves show the relative relaxation time of photoconductivity, which remains unchanged at certain bulk lifetimes and depths of macropores (see Figures 4 to 9). The color spectrum between the white curves shows the change in the relative relaxation time of photoconductivity. Each color shows the dependence of relative relaxation time of photoconductivity in the interval between the white curves. A grid of black on a plane shows two series of curves of the dependence of the relative relaxation time of photoconductivity (see Figures 4 to 9). The first series of curves is the dependence of relative relaxation time of photoconductivity on the bulk lifetime at a fixed pore depth. The second series of curves is the dependence of relative relaxation time of photoconductivity on the pore depth for a fixed bulk lifetime. The relative relaxation time of photoconductivity in a sample of macroporous silicon decreases if the bulk lifetime or the pore depth increases (see Figures 4 to 9). Let us explain this. The relative relaxation time of photoconductivity is determined from expression (23), rewritten as follows:

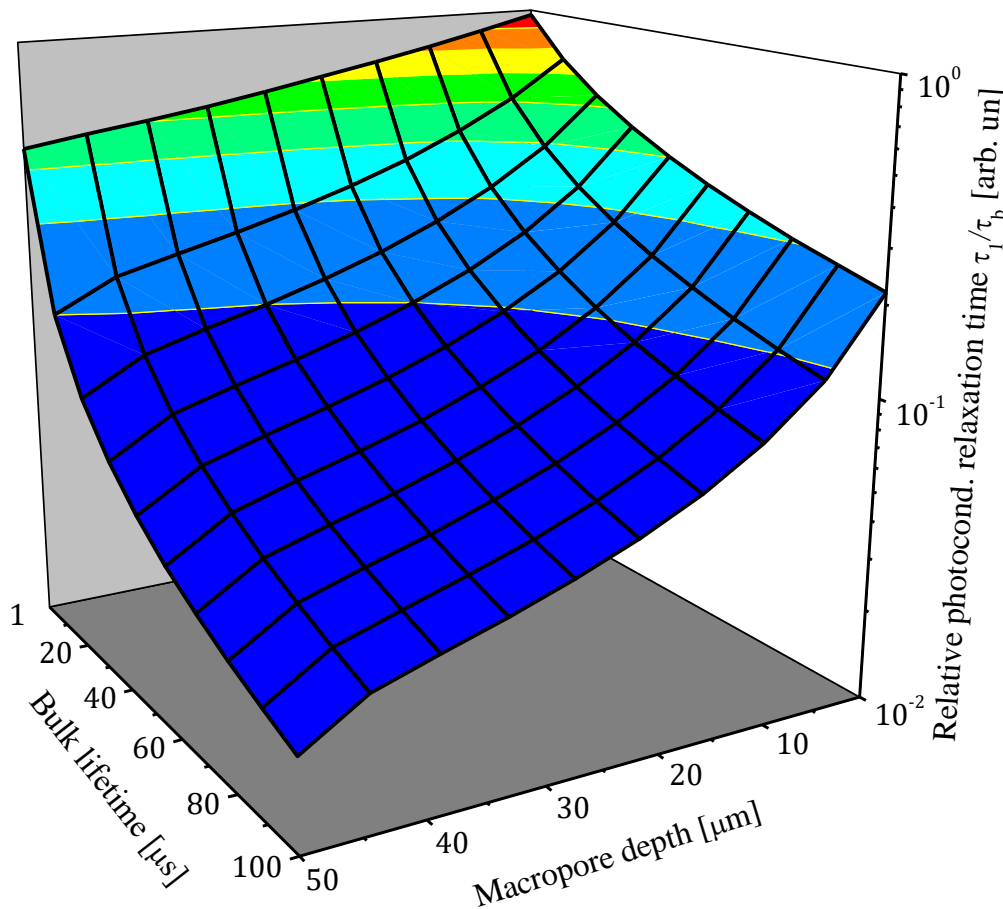$$\frac{\tau_1}{\tau_b} = \frac{1}{1 + \tau_b D_p a_s^2} \qquad (24)$$



**Figure 4. The dependence of the relative relaxation time of photoconductivity on the depth of the macropores and the bulk lifetime at thickness of macroporous silicon is 50 µm.**

The characteristic number $a_s$ characterizes the influence of surface and does not depend on bulk lifetime. It depends on the sample thickness, pore depth, surface recombination rate, diffusion coefficient, and other quantities, as can be seen from expressions (19-22). It can be seen from expression (24) that the bulk lifetime and characteristic number as are in the denominator; therefore, with an increase in these values, the relative relaxation time of photoconductivity in macroporous silicon will decrease, which we observe in Figures 4 to 9. The characteristic number $a_s$ is proportional to the surface recombination rate, as can be seen from expressions (19-22). It grows with increasing depth of macropores, because recombination on the surface of macropores increases with increasing depth of macropores.

Consider the first series of curves. Two characteristic dependences of the relative relaxation time of photoconductivity on the bulk lifetime are distinguished in the first series of curves. The depth of the macropores and the thickness of the macroporous silicon sample are considered as parameters in this series of curves. The first dependence is the dependence of the relative relaxation time of photoconductivity on the bulk lifetime in the absence of pores, $h_{por}=0$. This is the dependence for a single crystal. The second dependence is the dependence of the relative relaxation time of photoconductivity on the bulk lifetime at the pore depth (thickness of the macroporous layer) equal

to the thickness of the macroporous silicon sample $h_{por}=h$. This dependence is for macroporous silicon with through pores. The dependence of the relative relaxation time of photoconductivity on the bulk lifetime decreases with increasing bulk lifetime, both for a single crystal and for macroporous silicon with through pores. This has been explained above. The dependence of the relative relaxation time of photoconductivity on the bulk lifetime in a single crystal increases with increasing thickness of the sample (see Figures 4 to 9). Let us explain this. The thicknesses $h_0$ and $h_1$ are equal to half the thickness of the single crystal $h_1=h_0=h/2$, since the problem will be symmetric in this case. The characteristic number as is inversely proportional to the thickness of the single crystal, as can be seen from expressions (19), (22), therefore, with an increase in the thickness of the single crystal, the relative relaxation time of the photoconductivity increases (see Figures 4 to 9). The plane of the dependence of the relative relaxation time of photoconductivity on the bulk lifetime and the depth of the macropores rises with increasing thickness of the macroporous silicon. At the same time, the curve of the relative relaxation time of photoconductivity with through pores is the same in all Figures 4 to 9. The relative relaxation time of photoconductivity in macroporous silicon with through pores is 0.02 when $\tau_b = 100$ μm, as can be seen in Figures 4 to 9. Let us explain this. The relative relaxation time of photoconductivity for macroporous silicon with through pores is determined from expressions (21) and (23), as follows:

$$\frac{\tau_1}{\tau_b} = \frac{1}{1 + \tau_b \left( \dfrac{\pi D_{por} s_{por}}{a^2 - 0.25 \pi D_{por}^2} + D_p a_s^2 \right)} \tag{24}$$
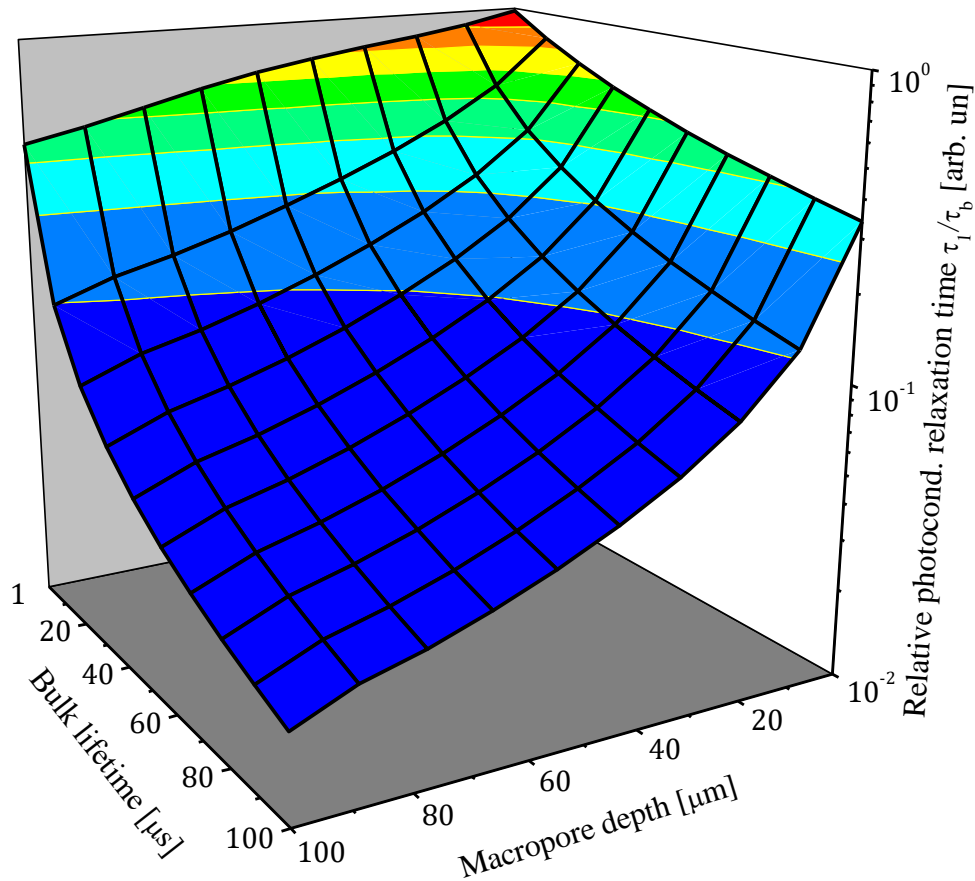


**Figure 5. The dependence of the relative relaxation time of photoconductivity on the depth of the macropores and the bulk lifetime at thickness of macroporous silicon is 100 μm.**

Let us consider macroporous silicon with through pores as an effective medium. The effective lifetime of minority charge carriers in a layer of macroporous silicon acts as the bulk lifetime in macroporous silicon with through pores. We replaced the bulk lifetime $\tau_b$ in expression (23) with the effective lifetime of minority charge carriers in the macroporous silicon layer $\tau_2$ from expression (21), and then divided it by the bulk lifetime $\tau_b$. Thus, we found the relative relaxation time of photoconductivity for macroporous silicon with through pores. Expression (24) is similar to expression (23), but in parentheses in the denominator contains an additional expression associated with through pores. If the first term in brackets of expression (24) is much larger than the second, then the relative relaxation time of photoconductivity in macroporous silicon with through pores will not depend on the thickness of the sample.
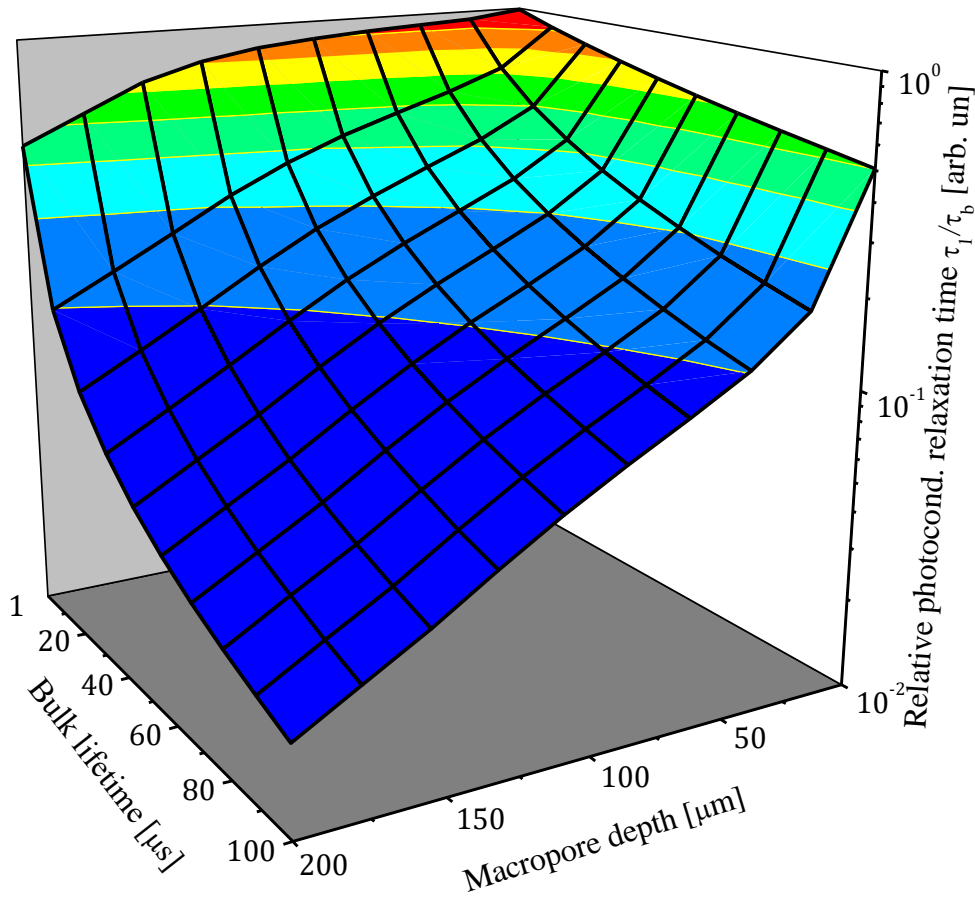
**Figure 6.** The dependence of the relative relaxation time of photoconductivity on the depth of the macropores and the bulk lifetime at thickness of macroporous silicon is 200 μm.

In Figures 4 to 9, we observe just this case. A series of curves of the dependence of the effective relaxation time of photoconductivity in a single crystal on the bulk lifetime, which is associated with a change in the thickness of the sample, passes into an invariable curve of the relaxation time of photoconductivity in macroporous silicon with through pores.

We consider the second series of curves, which is the dependence of the relative relaxation time of photoconductivity on the pore depth for a fixed bulk lifetime. The relative relaxation time of photoconductivity decreases with increasing depth of the macropores, as can be seen from Figures 4 to 9. Let us explain this decrease in the photoconductivity relaxation time. If the right-hand side of expressions (19) and (22) is greater than one, then we can write approximately $a_s h_0 \approx \pi/2$, $a_s h_1 \approx \pi/2$. Adding these two expressions, we obtain the following expression $a_s \approx \pi/(h_0+h_1) = \pi/(h-h_{por})$. The relative relaxation time of photoconductivity is determined from expression (23) as follows:

$$\frac{\tau_1}{\tau_b} = \frac{1}{1 + \tau_b D_p \left( \dfrac{\pi}{h - h_{por}} \right)^2} \tag{24}$$

The relative relaxation time of photoconductivity does not depend on the surface recombination rate, despite the fact that it is high on the surface of pores. The relative relaxation time of photoconductivity has a quadratic dependence on the substrate thickness, which depends on the depth of the pores, which can be seen from expression (24). A quadratic dependence of the relative photoconductivity relaxation time on the pore depth is visible in Figures 4 to 6, in samples from 50 to 200 μm thick, when recombination processes on the surface dominate, but the delivery of excess charge carriers to the surface is limited by diffusion. Note that when the pore depth increases, then the thickness of the single crystal substrate decreases. In Figures 7 to 9, the quadratic dependence of the relative relaxation time of photoconductivity on the pore depth is visible only at a small pore depth.
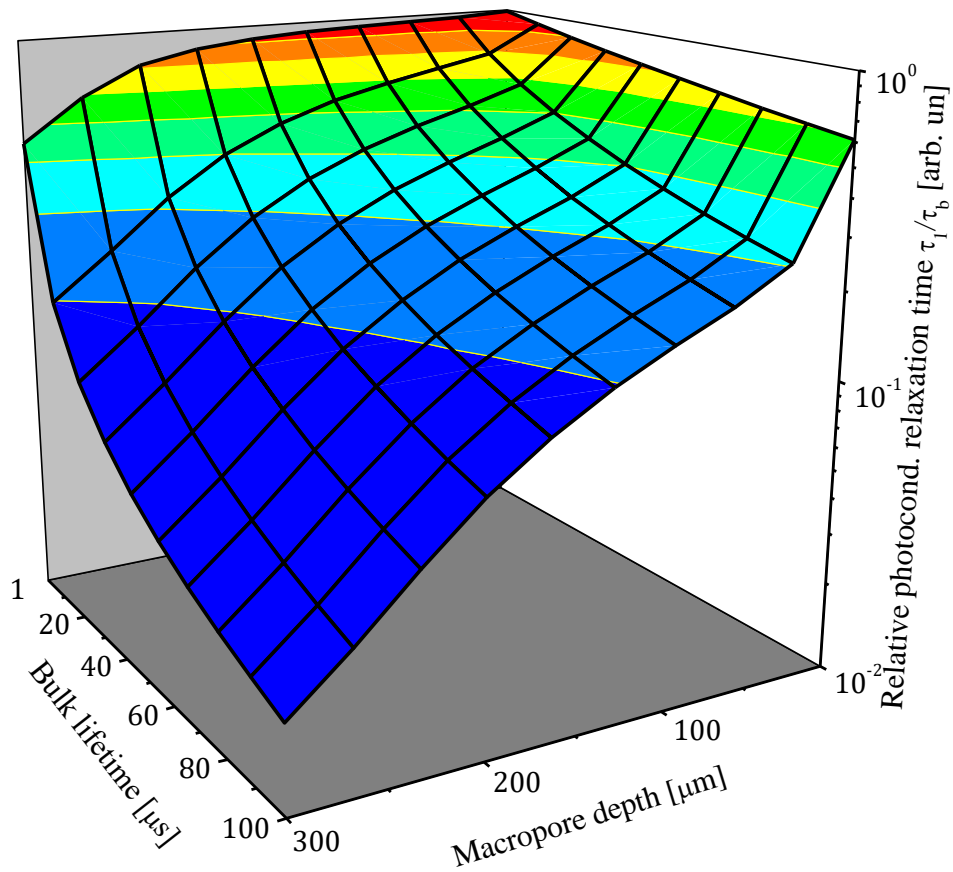
**Figure 7.** The dependence of the relative relaxation time of photoconductivity on the depth of the macropores and the bulk lifetime at thickness of macroporous silicon is 300 μm.



**Figure 8.** The dependence of the relative relaxation time of photoconductivity on the depth of the macropores and the bulk lifetime at thickness of macroporous silicon is 400 μm.
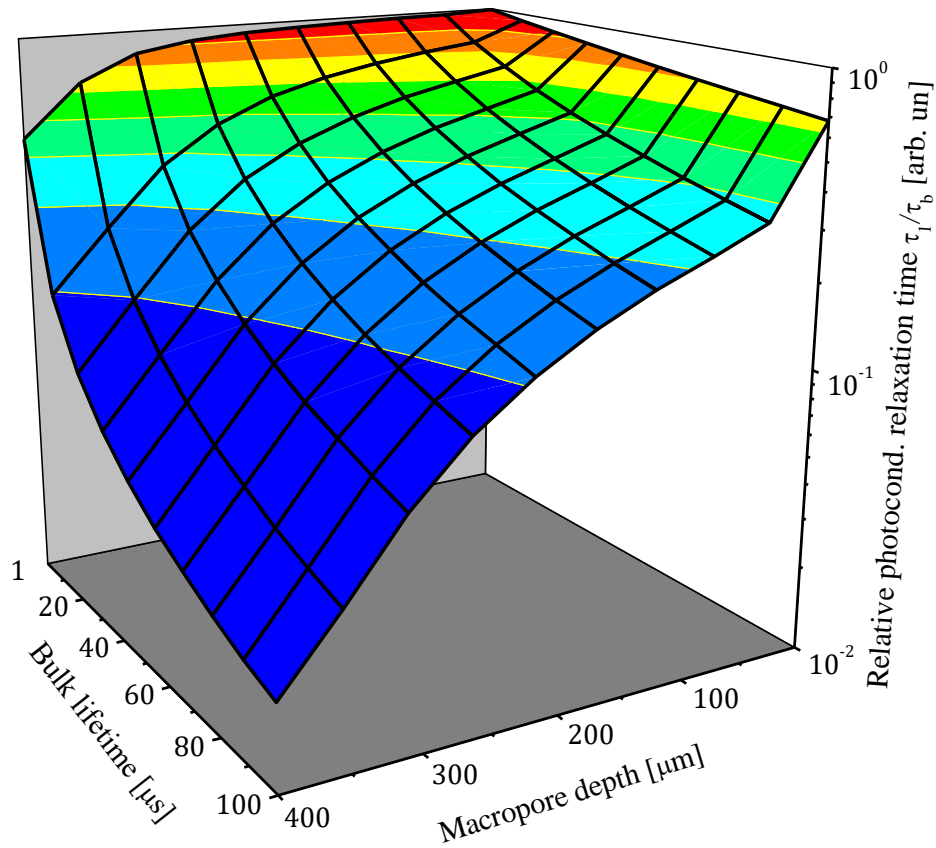
**Figure 9.** The dependence of the relative relaxation time of photoconductivity on the depth of the macropores and the bulk lifetime at thickness of macroporous silicon is 500 μm.
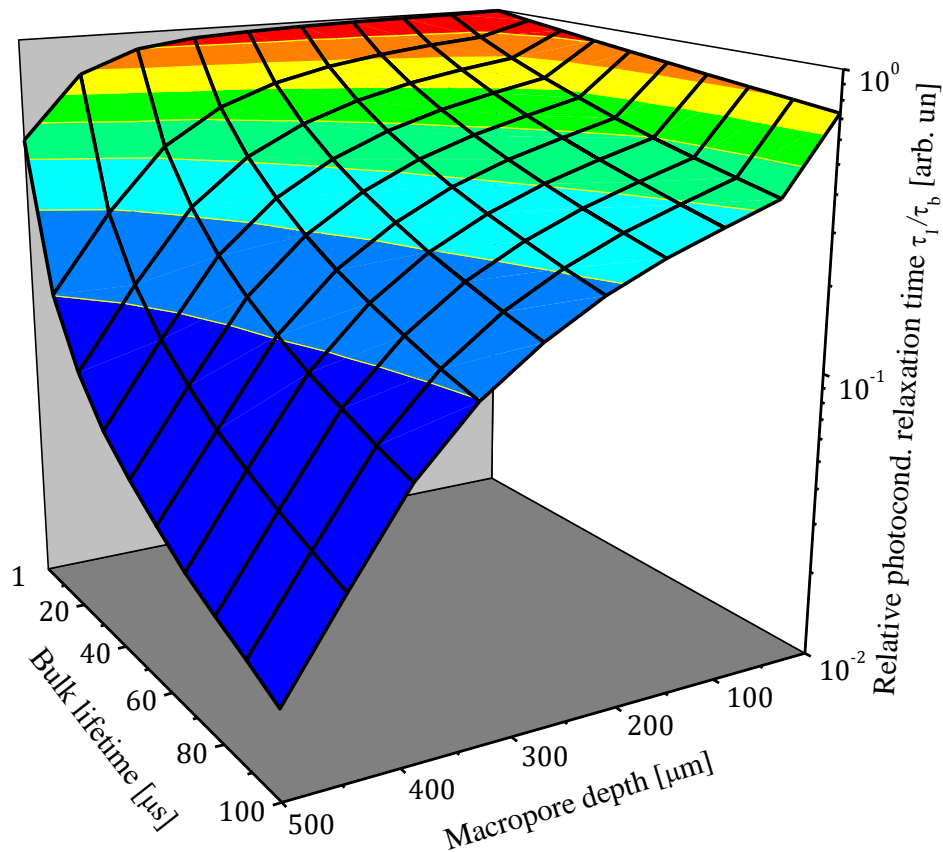
If the thickness of maroporous silicon is much greater than three diffusion lengths of charge carriers, then recombination in the sample bulk of macroporous silicon begins to influence the relative relaxation time of photoconductivity. Recombination in the bulk of a sample of macroporous silicon is characterized by the bulk lifetime. Excess charge carriers that are located at a distance equal to the diffusion length of the charge carriers from the macroporous silicon layer and the outer surface of the single crystal substrate will recombine the samples in bulk. That is, the bulk carrier lifetime will play an increasing role in influencing recombination with increasing sample thickness. We will no longer have a quadratic dependence of the relative relaxation time of photoconductivity on the thickness of the sample. These two dependencies, quadratic and non-quadratic, will compete with each other, which explains the further decrease in the photoconductivity recombination time with increasing depth of the macropores, which we observe in Figures 7 to 9.

Thus, the recombination in a layer of macroporous silicon increases with increasing area of macropores. If the recombination in the layer of macroporous silicon becomes very high, then it is limited by the diffusion of charge carriers from the single crystal substrate and the thickness of the single crystal substrate. We are the quadratic dependence of the relative relaxation time of photoconductivity on pore depth. If the sample thickness is much greater than three diffusion lengths of charge carriers, then the recombination in the bulk is commensurate with the recombination in the macroporous silicon layer, which is limited by the diffusion of charge carriers.

## 4- Conclusion

The photoconductivity recombination time in macroporous silicon is found from a system of two equations. The first equation describes the diffusion of excess charge carriers and their recombination in a layer of macroporous silicon and recombination at the interface of the layer of macroporous silicon and the single crystal substrate. The second equation describes diffusion of excess charge carriers to the surface and their recombination at the surface of the single crystal substrate. The system of transcendental equations that we have found will find application in calculating the relaxation time of photoconductivity in macroporous silicon devices such as sensors, receivers, and solar cells.

The photoconductivity recombination time in macroporous silicon is affected by bulk recombination, which is characterized by bulk minority carrier lifetime, and diffusion, which is characterized by carrier diffusion coefficient. Also, surface recombination affects the photoconductivity relaxation time; it depends on the surface recombination

rate, the thickness of the single crystal substrate and the characteristics of the macroporous layer: the depth of the macropores, the average diameter of the macropores, the average distance between the centers of the macropores, and the volume fraction of the macropores.

The photoconductivity recombination time in the sample of macroporous silicon is limited by the diffusion of charge carriers from the substrate to the recombination surfaces in the macroporous layer, if the diffusion time of excess charge carriers to the recombination surfaces of the macroporous silicon layer longer the effective recombination time of excess charge carriers in the macroporous silicon layer.

## 5- Funding

## 6- Conflict of Interest

The author declares that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

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