Journal of Nano- and Electronic Physics
Vol. **16** No 4, 04026(7pp) (2024)

Журнал нано- та електронної фізики
Том **16** № 4, 04026(7cc) (2024)

REGULAR ARTICLE

Effective Minority Carrier Lifetime in Double-Layer Macroporous Silicon

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(Received 10 May 2024; revised manuscript received 15 August 2024; published online 27 August 2024)

The effective minority carrier lifetime in double-layer macroporous silicon is calculated according to analytically derived equations. The solution of the diffusion equation of minority carriers is written for a monocrystalline substrate and layers of macroporous silicon. The boundary condition is written for the surfaces of the first layer of macroporous silicon and the monocrystalline substrate. The system of seven equations is analytically reduced to two transcendental equations, which are used to calculate the effective minority carrier lifetime in double-layer macroporous silicon. The dependence of the effective minority carrier lifetime in double-layer macroporous silicon on the thickness of macroporous silicon and the depth of macropores of each layer of macroporous silicon was analyzed. The effective minority carrier lifetime in double-layer macroporous silicon depends on bulk lifetime of minority carriers, surface recombination, which depends on the average macropore diameter, average macropore depth, and average distance between macropores, and diffusion.

Keywords: Effective minority carrier lifetime, Double-layer macroporous silicon, Macroporous silicon.

DOI: 10.21272/jnep.16(4).04026 PACS number: 78.20. – e

1. INTRODUCTION

Macroporous silicon, nanowires, pyramids, and structured surfaces have a large recombination area that affects the effective minority carrier lifetime. A model was developed for calculating the effective minority carrier lifetime in macroporous silicon. The effective lifetime in macroporous silicon with periodically arranged macropores and through-pores is calculated. The calculations are compared with the experimentally measured effective lifetime of minority carriers in macroporous silicon with thermal oxidation [1]. The optical and electronic properties of black silicon are studied. The texture of black silicon was formed by plasma chemical vapor deposition. Nanostructured monocrystalline black silicon is passivated by depositing an atomic layer of aluminum oxide on the structured surface. The surface recombination velocity of passivated black silicon was equal to 0.13 m/s. The minority carrier lifetime in black silicon is milliseconds. Black silicon demonstrates high efficiency in converting solar energy into electrical energy [2]. The photoconductivity of bilateral macroporous silicon is calculated using the diffusion model. The macropores have a large recombination area, so the photoconductivity of the bilateral macroporous silicon decreases as the macropore depth of the macroporous silicon layer increases. The photoconductivity of bilateral macroporous silicon decreases when the bulk lifetime of minority carriers decreases [3]. The surface structured by nanowires is passivated with silicon oxide. The oxide has a fixed charge. The concentration of charge carriers in silicon nanowires is determined by the radius of the nanowire, the charge concentration in the oxide, and the concentration of alloying impurities. The concentration of charge carriers in silicon nanowires is completely depleted at a certain critical radius. The formula for this critical radius of a nanowire is derived [4]. The kinetics of charge carriers in bilateral macroporous silicon is calculated using the diffuse model. The macropore depth of the macroporous silicon layers is the same. The excess carrier concentration sharply decreases in the layers of macroporous silicon after their generation is turned off. Excess charge carriers diffuse from the monocrystalline substrate and recombine on the surface of the macropores [5]. The mobility of electrons and holes in nanowires has a lower mobility than the mobility of electrons in the bulk material. The mobility curves of electrons and holes in silicon crystalline nanowires are closer to the surface mobility curves than to the volume mobility curves [6]. The kinetics of photoconductivity in bilateral macroporous silicon is calculated by the finite difference method. The thickness of macroporous silicon is 500 µm. The depth of macropores of the layer of macroporous silicon is 100 µm, the depth of the second layer of macroporous silicon varies. The initial relaxation period of photoconductivity depends on the depth of the macropores of both layers of macroporous silicon [7]. The current-voltage and capacitance characteristics of Schottky barriers on single-crystal silicon nanowires are measured. Nanowires are grown on p-type silicon by chemical etching with gold. The metal-semiconductor-metal model is used to analyze current-current and capaci-

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Cite this article as: V.F. Onyshchenko, *J. Nano- Electron. Phys.* 16 No 4, 04026 (2024) https://doi.org/10.21272/jnep.16(4).04026

tance characteristics. The transport properties of electrons are explained by the thermoelectron emission method. The volt-capacity characteristics of silicon nanowires show the presence of space charge regions [8]. The porous silicon layers were separated from the monocrystalline silicon substrate using epoxy resin. The processes of charge transfer and relaxation are studied using the methods of impedance and thermal activation spectroscopy. At temperatures from 270-350 K, an activation mechanism of conductivity is observed. Localized electronic states were detected using spectra of thermally stimulated depolarization. The energy distribution of the density of filling states with electrons has a maximum in the range of 0.45-0.6 eV. Electron capture levels are related to defects at the interface between the nanocrystals and the epoxy resin [9]. The resistivity of p-type porous silicon depends on the physical properties of porous silicon. Al/PS/Si/Al structures were used to determine resistance. The resistivity of p-type porous silicon is thermally activated. The specific resistance decreases with increasing temperature from 30 to 200 C. Mechanisms of transport of charge carriers in porous silicon are shown. The transport of charge carriers occurs through the tails of the conduction band bands and deep energy levels. At a volume fraction of pores greater than 45 %, a conductivity jump between crystallites appears [10]. Surfaces structured with nanowires are present in solar cells to reduce the reflection of light from its surface. An increase in surface area increases recombination on the surface of nanodots and reduces the efficiency of conversion of solar energy into electricity. The influence of various passivated surfaces on effective surface recombination is experimentally analyzed. The influence of the surface concentration of a fixed charge on the silicon oxide silicon boundary is shown [11]. The reflectance of nanowires and macroporous silicon was calculated using the analytical model of the reflection of a double-layer structure. The total internal reflection of light from the surface of a monocrystalline substrate with a macroporous layer is taken into account. The reflectance of macroporous silicon decreases as the volume fraction of pores increases. The complex effective refractive index is used to calculate the reflectance of macroporous silicon surfaces [12]. Arrays of nanowires on the surface of silicon films with a thickness of 8 μm show the best ratio between improved absorption and reduced photocurrent due to the rate of surface recombination [13]. The optical reflectance, short-circuit current and quantum efficiency of solar cells based on silicon nanowires are measured. The reflection coefficient of silicon nanowires decreases by an order of magnitude compared to a flat surface [14]. Absorption and transmittance of nanowires and bilateral macroporous silicon are calculated using derived formulas. Absorption and transmission increase due to the decrease in reflectance of the surfaces of macroporous layers when the volume fraction of pores increases. The transmittance of the lateral surfaces of bilateral macroporous silicon was calculated [15].

2. THE EFFECTIVE MINORITY CARRIER LIFETIME IN DOUBLE-LAYER MACROPOROUS SILICON

Fig. 1 shows a scheme of double-layered macroporous silicon with a thickness of h or nanowires with two diameters on a monocrystalline substrate. On the monocrystalline silicon substrate, macropores are etched that up to a depth of h_1 have a volume fraction of pores P_1 (the outer (first) layer of macroporous silicon), and from a depth of h_1 to a depth of h_2 have a volume fraction of macropores of P_2 (the inner (second) layer macroporous silicon).

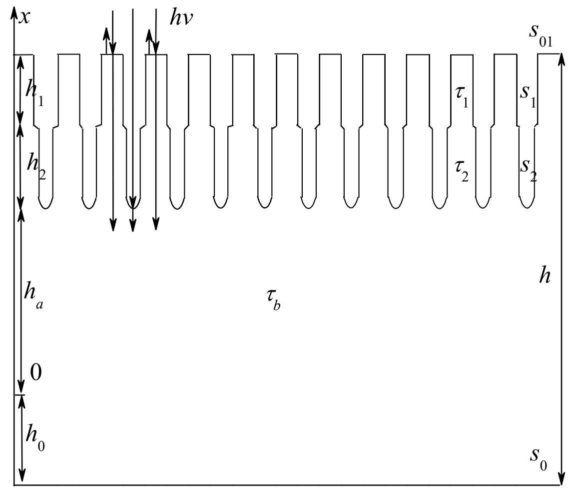

Fig. 1 – Scheme of double-layer macroporous silicon or nanowires with two diameters on a monocrystalline substrate

Let $\delta p_1(x, t)$, $\delta p_2(x, t)$, $\delta p_m(x, t)$ be the excess minority carrier concentration in the first and second layers of macroporous silicon and the monocrystalline substrate, respectively. Here, x is a coordinate, t is time. The excess minority carrier concentration will have a maximum in the monocrystalline substrate after the termination of the generation of excess minority charge carriers, after a time greater than the effective minority carrier lifetime $t >> \tau_{eff}$. The origin of the coordinates is selected at the point of the maximum. The boundary of the monocrystalline substrate with the second layer of macroporous silicon has the coordinate ha. The boundary of a monocrystalline substrate with air has a coordinate of $-h_0$. The boundary condition at the boundary between the second and the first layers of macroporous silicon:

$$\begin{aligned}&(1-P_1)j_{p12}(h_{a2},t)-(1-P_2)j_{p21}(h_{a2},t)=\\&=s_1(P_1-P_2)\delta p_2(h_{a2},t)\end{aligned}, \quad (2.1)$$

where $h_{a2} = h_a + h_2$. The value of the diffusion current density of excess minority charge carriers in the first and second layers of macroporous silicon, at the boundary between the first and second layers of macroporous silicon, are written as follows:

$$j_{p1}(h_{a2},t)=-D_p\frac{\partial}{\partial x}\delta p_1(h_{a2},t)\,, \quad (2.2)$$

$$j_{p2}(h_{a2},t)=-D_p\frac{\partial}{\partial x}\delta p_2(h_{a2},t)\,. \quad (2.3)$$

The values of the excess minority carrier concentration in the first and second layers of macroporous silicon must be equal at the boundary between the first and second layers of macroporous silicon:

$$p_1(h_{a2},t) = p_2(h_{a2},t) \,. \quad (2.4)$$

From expressions (2.1)-(2.4), the boundary condition at the boundary between the second and first layers of macroporous silicon is written as follows:

$$\frac{1-P_1}{1-P_2}\frac{\frac{\partial}{\partial x}\delta p_1(h_{a2},t)}{\delta p_1(h_{a2},t)} - \frac{\frac{\partial}{\partial x}\delta p_2(h_{a2},t)}{\delta p_2(h_{a2},t)} = \frac{s_1(P_1-P_2)}{D_p(1-P_2)} \,. \quad (2.5)$$

The boundary condition at the boundary between the monocrystalline substrate and the second layer of macroporous silicon:

$$(1-P_2)j_{p2}(h_a,t) - j_{pm}(h_a,t) = P_2 s_2 \delta p_m(h_a,t) \,. \quad (2.6)$$

The value of the diffusion current density of excess minority charge carriers in the second layer of macroporous silicon and the monocrystalline substrate, at the boundary of the second layer of macroporous silicon with the monocrystalline substrate, are written as follows:

$$j_2(h_a,t) = -D_p \frac{\partial}{\partial x}\delta p_2(h_a,t) \,, \quad (2.7)$$

$$j_{pm}(h_a,t) = -D_p \frac{\partial}{\partial x}\delta p_m(h_a,t) = \\ = D_p \delta p_m(h_a,t) a_s \tan(a_s h_a) \,, \quad (2.8)$$

where the excess minority carrier concentration in a monocrystalline substrate is represented as: $p_m(x, t) = A_1\exp(-t/\tau_{eff})\cos(a_s x)$ [7]. The values of the excess minority carrier concentrations in the second layer of macroporous silicon and in the monocrystalline substrate must be equal at the boundary of the second layer of macroporous silicon with the monocrystalline substrate:

$$p_2(h_a,t) = p_m(h_a,t) \,. \quad (2.9)$$

Boundary conditions at the boundary of the first layer of macroporous silicon with air and a monocrystalline substrate with air are written as:

$$s_{01}\delta p_1(h_{a1},t) = D_p \frac{\partial}{\partial x}\delta p_1(h_{a1},t) \,, \quad (2.10)$$

$$s_0 \delta p_m(h_0,t) = D_p \frac{\partial}{\partial x}\delta p_2(h_0,t) = \\ = D_p \delta p_m(h_0,t) a_s \tan(a_s h_0) \,, \quad (2.11)$$

where $h_{a1} = h_a + h_2 + h_1$, s_{01}, s_0 are surface recombination velocities at the boundary of the first layer of macroporous silicon with air and at the boundary of the monocrystalline substrate with air. From expressions (2.5)-(2.8), the boundary condition at the boundary of the monocrystalline substrate with the second layer of macroporous silicon is written as:

$$a_s \tan(a_s h_a) = \left(\frac{P_2 s_{por2}}{D_p} - (1-P_2)\frac{\frac{\partial}{\partial x}\delta p_2(h_a,t)}{\delta p_2(h_a,t)} \right) . \quad (2.12)$$

Boundary conditions in double-layer macroporous silicon, expressions (2.4), (2.5), (2.9)-(2.12), are a system of equations. The excess minority carrier concentrations in the first and second layers of macroporous silicon are written in the form: $p_1(x,t) = \exp(-t/\tau_{eff})(C_{11}\exp(x/L_1) + C_{12}\exp(-x/L_1))$, $p_2(x,t) = \exp(-t/\tau_{eff})(C_{21}\exp(x/L_2) + C_{22}\exp(-x/L_2))$. Here, C_{11}, C_{12}, C_{21}, C_{22} are constants, τ_{eff} is the effective minority carrier lifetime in double-layer macroporous silicon, L_1, L_2 are diffusion lengths in the first and second layers of macroporous silicon. The ratio of the derivative of the functions to the functions in the first layer of macroporous silicon is written as follows:

$$\frac{\frac{\partial}{\partial x}\delta p_1(x,t)}{\delta p_1(x,t)} = \frac{1}{L_1}\left(1 - \frac{2}{\frac{C_{11}}{C_{12}}\exp\left(\frac{2x}{L_1}\right)+1}\right) . \quad (2.13)$$

The ratio of the derivative of the functions to the functions in the second layer of macroporous silicon is written similarly. Using expression (2.13), expression (2.5) is written as:

$$\frac{1-P_1}{1-P_2}\frac{L_2}{L_1}\left(1 - \frac{2}{\frac{C_{11}}{C_{12}}\exp\left(\frac{2h_{a2}}{L_1}\right)+1}\right) - 1 + \\ + \frac{2}{\frac{C_{21}}{C_{22}}\exp\left(\frac{2h_{a2}}{L_2}\right)+1} = \frac{s_1 L_2(P_1-P_2)}{D_p(1-P_2)} \,. \quad (2.14)$$

From expressions (2.11) and (2.13), the C_{11}/C_{12} ratio is written as:

$$\frac{C_{11}}{C_{12}} = \exp\left(\frac{-2h_{a1}}{L_1}\right)\left(\frac{1-S_{01}}{S_{01}+1}\right) , \quad (2.15)$$

where $S_{01} = s_0 1 L_1/D_p$ is the dimensionless velocity of surface recombination, where D_p is the diffusion coefficient. Using expression (2.13), expression (2.10) is written as:

$$a_s \tan(a_s h_a) = \frac{P_2 S_2}{L_2} - \frac{1-P_2}{L_2}\left(1 - \frac{2}{\frac{C_{21}}{C_{22}}\exp\left(\frac{2h_a}{L_2}\right)+1}\right) . \quad (2.16)$$

Using expressions (2.14), (2.15), expression (2.16) is written as follows:

$$\tan(a_s h_a) = \frac{P_2 S_2}{a_s L_2} + \frac{S_{2*}(1-P_2)}{a_s L_2} \,. \quad (2.17)$$

The dimensionless surface velocity of disappearance of minority charge carriers at the boundary of a monocrystalline substrate with a monocrystalline silicon matrix of the second layer of macroporous silicon is written as follows:

$$S_{2*} = \frac{2}{1-\exp\left(\frac{2h_2}{-L_2}\right)\left(1 - \frac{2}{1 - \frac{L_2}{L_1}\frac{1-P_1}{1-P_2}S_{1*} + S_{12}\frac{P_1-P_2}{1-P_2}}\right)} - 1 \,. \quad (2.18)$$

The dimensionless surface velocity of disappearance of minority charge carriers at the boundary of the monocrystalline silicon matrix of the second layer of macroporous silicon with the monocrystalline silicon matrix of the first layer of macroporous silicon is written as follows:

$$S_{1*} = 1 - \frac{2}{1 - \exp\left(\frac{2h_1}{-L_1}\right)\frac{S_{01}-1}{S_{01}+1}} . \quad (2.19)$$

Expression (2.11) is rewritten as:

$$\tan(a_s(h - h_a - h_1 - h_2) = \frac{s_0}{D_p a_s} = \frac{S_0}{L_p a_s} . \quad (2.20)$$

The value a_s is found from the system of two equations (2.17) and (2.20). The effective minority carrier lifetime is as follows:

$$T_{ml} = \frac{I_{lT}(h_m)(1 - R_{s2*})(1 + R_{s3} I_b(h_m))}{1 - R_{s2} R_{s3} I_b^2(h_m)} , \quad (2.21)$$

3. RESULTS AND DISCUSSION

Fig. 2 shows the dependence of the effective minority carrier lifetime in double-layer macroporous silicon with a thickness of 500 μm on the depth of macropores of the first (varies from 0 to 250 μm) and second layers of macroporous silicon with different effective lifetimes of minority charge carriers in the first layer of macroporous silicon. The effective minority carrier lifetime in the second layer of macroporous silicon is 1 μs.

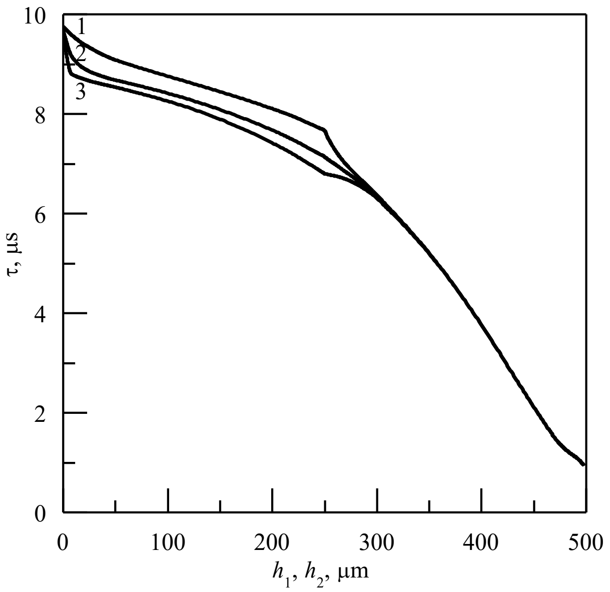

Fig. 2 – The effective minority carrier lifetime in double-layer macroporous silicon depending on the depth of macropores of the first (varies from 0 to 250 μm) and second layers of macroporous silicon, when the effective minority carrier lifetime in the first layer of macroporous silicon, μs: 1–8; 2–1; 3–0.1. The effective minority carrier lifetime in the second layer of macroporous silicon is 1 μs

The diameter of the macropores, the average distance between them, and the surface recombination velocity on the surface of the macropores correspond to the effective minority carrier lifetime in each layer of macroporous silicon. The surface recombination velocity on the surface of double-layer macroporous silicon is 0.9 m/s. The effective minority carrier lifetime in double-layer macroporous silicon is calculated according to expressions (2.18)-(2.21). The depth of the macropores of the first layer of macroporous silicon varies from zero (single crystal silicon) to 250 μm, when there is no second layer of macroporous silicon. The effective lifetime of the first layer of macroporous silicon determines the effective minority carrier lifetime in double-layer macroporous silicon. This is due to the fact that the first layer of macroporous silicon has a boundary with a monocrystalline substrate. Excess carriers diffuse from the monocrystalline substrate to the recombination centers on the surface of the macropores. An increase in the depth of macropores increases the area of surface recombination of macropores. Curve 2 in Fig. 2 shows the dependence of the effective minority carrier lifetime in double-layer macroporous silicon on the depth of macropores, when the effective minority carrier lifetimes in the second and first layers of macroporous silicon are the same. The diameters of the macropores of each layer of macroporous silicon are different, but due to the corresponding surface recombination velocity on the surface of the macropores, the effective minority carrier lifetime in the first and second layers of macroporous silicon is the same. The effective minority carrier lifetime in double-layer macroporous silicon decreases when the depth of the macropores of the first and second layers of macroporous silicon increases. Curves 1-3 in Fig. 2 converge to one curve with the increase in the depth of the macropores of the second layer of macroporous silicon. The effective minority carrier lifetime in the second layer of macroporous silicon determines the effective minority carrier lifetime in double-layer macroporous silicon. The second layer of macroporous silicon has an interface with the monocrystalline substrate, so it determines the effective lifetime minority carrier lifetime in the double-layer macroporous silicon.

Fig. 3 shows the dependence of the effective minority carrier lifetime in double-layer macroporous silicon with a thickness of 500 μm on the depth of the macropores of the first (varies from 0 to 250 μm) and the second layers of macroporous silicon with different effective lifetimes of minority charge carriers in the second layer of macroporous silicon. The effective minority carrier lifetime in the first layer of macroporous silicon is 1 μs. The diameter of the macropores, the average distance between them, and the surface recombination velocity on the surface of the macropores correspond to the effective minority carrier lifetime in each layer of macroporous silicon. The surface recombination velocity on the surface of double-layer macroporous silicon is 0.9 m/s. The depth of the macropores of the first layer of macroporous silicon varies from zero (single crystal silicon) to 250 μm, when there is no second layer of macroporous silicon. The effective minority carrier lifetime in double-layer macroporous silicon decreases when the depths of the macropores of the first and second layers of macroporous silicon increase. Curve 4 in Fig. 3 shows the dependence of the effective minority carrier lifetime in double-layer macroporous silicon on the depth of macropores, when the effective minority carrier lifetimes in the second and first layers of macroporous silicon are the same. The effective minority carrier lifetime in double-layer macroporous silicon increases to 4.7 μs, 3.5 μs, 2.7 μs at a macropore depth of 450 μm (see Fig. 3, curves 1–3, respectively).

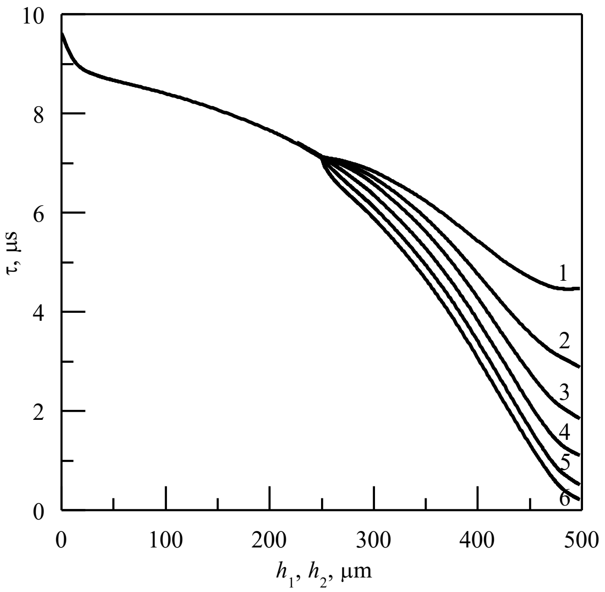

Fig. 3 – The effective minority carrier lifetime in double-layer macroporous silicon depending on the depth of the macropores of the first (varies from 0 to 250 μm) and second layers of macroporous silicon, when the effective lifetime in the second layer of macroporous silicon, μs: 1–8; 2–4; 3–2; 4–1; 5–0.5; 6–0.1. The effective minority carrier lifetime in the first layer of macroporous silicon is 1 μs

An increase in the effective minority carrier lifetime in double-layer macroporous silicon occurs if the effective lifetime in the second layer of macroporous silicon is greater than in the first. The effective life time in double-layer macroporous silicon decreases to 1.6 μm, 1.3 μm at a macropore depth of 450 μm, if the effective life time in the second layer of macroporous silicon is less than in the first (see Fig. 3, curves 5, 6).

Fig. 4 shows the dependence of the effective minority carrier lifetime in double-layer macroporous silicon with a thickness of 500 μm on the depth of the macropores of the first and second layers of macroporous silicon at different depths of the macropores of the first layer of macroporous silicon. The effective minority carrier lifetime in the first and second layers of macroporous silicon is 8 μs and 0.1 μs, respectively. The diameter of the macropores, the average distance between them, and the surface recombination velocity on the surface of the macropores correspond to the effective minority carrier lifetime in each layer of macroporous silicon. The surface recombination velocity on the surface of double-layer macroporous silicon is 0.9 m/s. The depth of the macropores of the first layer of macroporous silicon varies from zero to the specified depth when the second layer of macroporous silicon is absent. The second layer of macroporous silicon has a shorter effective minority carrier lifetime, so the effective minority carrier lifetime in double-layer macroporous silicon decreases as the macropore depth of the second layer of macroporous silicon increases. As the depth of the macropores of the first layer of macroporous silicon increases, the effective minority carrier lifetime in double-layer macroporous silicon decreases by a greater value when the depth of the macropores of the second layer increases (see Fig. 4, curves 1–4). Curve 4 in Fig. 4 shows the effective minority carrier lifetime in double-layer macroporous silicon with a depth of macropores of the first layer of macroporous silicon up to 400 μm. Curve 1 in Fig. 4 shows the effective minority carrier lifetime in double-layer macroporous silicon with a depth of macropores of the second layer of macroporous silicon up to 400 μm. Curve 4 smoothly transitions to curve 1 when the macropores of the second layer of macroporous silicon appear (see Fig. 4, curves 1–4).

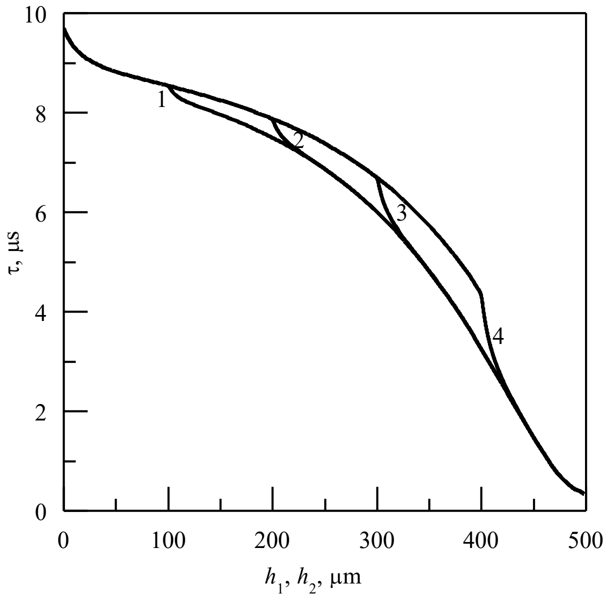

Fig. 4 – The effective minority carrier lifetime in double-layer macroporous silicon depending on the depth of the macropores of the first and second layers of macroporous silicon, when the depth of the macropores of the first layer of macroporous silicon, μm: 1–100; 2–200; 3–300; 4–400. The effective minority carrier lifetime in the first and second layers of macroporous silicon is 8 μs and 0.1 μs, respectively

Fig. 5 shows the dependence of the effective minority carrier lifetime in double-layer macroporous silicon with different thicknesses on the depth of the macropores of the first (varies from 0 to 150 μm) and the second layers of macroporous silicon. The effective minority carrier lifetime in the first and second layers of macroporous silicon is 2.5 μs and 0.3 μs, respectively. The diameter of the macropores, the average distance between them, and the surface recombination velocity on the surface of the macropores correspond to the effective lifetime of minor charge carriers in each layer of macroporous silicon. The surface recombination velocity on the surface of double-layer macroporous silicon is 0.9 m/s. The depth of the macropores of the first layer of macroporous silicon varies from zero to 150 μm, when there is no second layer of macroporous silicon. The maximum macropore depth of the second layer of macroporous silicon decreases as the thickness of the double-layer macroporous silicon decreases. The maximum depth of macropores of the first macroporous silicon is 150 μm. The effective minority carrier lifetime in double-layer macroporous silicon decreases with decreasing thickness of double-layer macroporous silicon. The dependence curves of the effective minority carrier lifetime in double-layer macroporous silicon on the depth of the macropores become less convex.

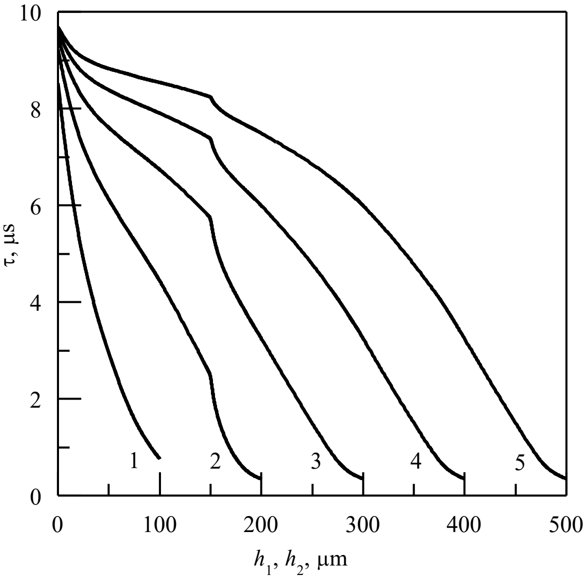

Fig. 5 – The effective minority carrier lifetime in double-layer macroporous silicon thickness, μm: 1–100; 2–200; 3–300; 4–400, 5–500, depending on the depth of macropores of the first (varies from 0 to 150 μm) and second layers of macroporous silicon. The effective minority carrier lifetime in the first and second layers of macroporous silicon is 2.5 μs and 0.3 μs, respectively

A rapid decrease in the effective minority carrier lifetime in double-layer macroporous silicon with an increase in the depth of macropores is observed when the first and second layers of macroporous silicon appear.

4. CONCLUSIONS

The effective minority carrier lifetime in double-layer macroporous silicon decreases with increasing depth of macropores of the first and second layers of macroporous silicon. The effective lifetime of the first layer of macroporous silicon determines the effective minority carrier lifetime in double-layer macroporous silicon before the appearance of the second layer of macroporous silicon. This is due to the fact that the first layer of macroporous silicon has a boundary with a monocrystalline substrate. Excess carriers diffuse from the monocrystalline substrate to the recombination centers on the surface of the macropores. An increase in the depth of macropores increases the area of surface recombination of macropores. The effective minority carrier lifetime in double-layer macroporous silicon decreases as the macropore depth of the second layer of macroporous silicon increases due to the fact that the second layer of macroporous silicon has a shorter effective minority carrier lifetime than that of the first layer of macroporous silicon. An increase in the effective minority carrier lifetime in double-layer macroporous silicon occurs if the effective lifetime in the second layer of macroporous silicon is greater than in the first. The effective minority carrier lifetime in the second layer of macroporous silicon determines the effective minority carrier lifetime in double-layer macroporous silicon. The second layer of macroporous silicon has an interface with the monocrystalline substrate, so it determines the effective lifetime minority carrier lifetime in the double-layer macroporous silicon.

The effective minority carrier lifetime in double-layer macroporous silicon decreases with decreasing thickness of double-layer macroporous silicon. The maximum depth of the macropores of the second layer of macroporous silicon decreases when the thickness of the double-layer macroporous silicon decreases, so the curves of the dependence of the effective minority carrier lifetime in double-layer macroporous silicon on the depth of the macropores decrease faster. A rapid decrease in the effective minority carrier lifetime in double -layer macroporous silicon is observed upon the appearance of the first and second layers of macroporous silicon.

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Ефективний час життя неосновних носіїв заряду в двошаровому макропористому кремнії

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Ефективний час життя неосновних носіїв заряду в двошаровому макропористому кремнії розраховано за аналітично виведеними рівняннями. Розв'язок рівняння дифузії неосновних носіїв заряду записується для монокристалічної підкладки та шарів макропористого кремнію. Гранична умова записується для поверхонь першого шару макропористого кремнію та монокристалічної підкладки. Система семи рівнянь аналітично зводиться до двох трансцендентних рівнянь, які використовуються для розрахунку ефективного часу життя неосновних носіїв заряду в двошаровому макропористому кремнії. Проаналізована залежність ефективного часу життя неосновних носіїв заряду в двошаровому макропористому кремнії від товщини макропористого кремнію та глибини макропор кожного шару макропористого кремнію. Ефективний час життя неосновних носіїв заряду в двошаровому макропористому кремнії залежить від об'ємного часу життя неосновних носіїв заряду, поверхневої рекомбінації, яка залежить від середнього діаметра макропор, середньої глибини макропор та середньої відстані між макропорами, та дифузії.

Ключові слова: Ефективний час життя неосновних носіїв заряду, Двошаровий макропористий кремній, Макропористий кремній.