Optics of Macroporous Silicon with Through Pores

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The paper presents the theory and calculation of transmission, reflection, and absorption of macroporous silicon with through pores. Macroporous silicon with through pores is considered as an effective medium, the surface of which scatters electromagnetic waves. Scattering by the surface of macroporous silicon is taken into account using the effective scattering angle. The effective complex refractive index and the effective absorption coefficient are calculated using the mixing formulas. Derived analytical formulas for calculating transmittance, reflection and absorption of macroporous silicon with through pores take into account multiple reflections from the inner sides of the front and back surfaces. The influence of the volume fraction of pores and the thickness of macroporous silicon with through-pores on its reflection, transmission, and absorption was analyzed. The reflection and transmittance of the front and back surfaces and the absorption by the effective volume of macroporous silicon depend on the volume fraction of pores and affect the optical properties of macroporous silicon with through pores.

Keywords: Macroporous silicon, Through-pores, Reflection, Absorption, Transmission.

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1. INTRODUCTION

Macroporous silicon is a single crystal of silicon with a structured surface with pores or protrusions. The optical properties of macroporous silicon and nanowires show a decrease in reflectance and an increase in light absorption. The reflectance spectra of macroporous silicon with pores or nanowires are calculated using the developed analytical model. The analytical model takes into account multiple reflections from the structured surfaces of the macroporous layer and the flat surface of the monocrystalline substrate. The reflection of macroporous silicon increases with a decrease in the volume fraction of pores [1]. Structural-luminescence analysis of macroporous silicon shows that the samples emit light with an external quantum efficiency of 15-20 %. Interface oxide centers make a significant contribution to radiative recombination. X-ray diffraction measurements indicate stress in the porous silicon layer [2]. Porous and macroporous silicon is an anti-reflective coating for solar cells. A layer of porous silicon reduces surface reflection from 30 % to 6 % [3]. The reflectivity of the porous coating is modelled using the effective medium theory. An array of paraboloids with a height of 0.3 μm and a distance between them of 30 nm is the optimal form of a structured surface [4]. Compact designs of high-power LED devices are created. The optimal dimensions of structural elements are calculated by computer modeling [5]. A new method of finding optimal peak wavelengths based on modeling the spectrum of the resulting radiation is proposed [6]. Macroporous silicon is used as a photonic crystal resonator. The field distribution for typical modes in the middle of the resonator and the photon zone of the resonator are calculated using the standing wave decomposition method [7]. Defects in the structure of macroporous silicon, differences in the periodicity of location and radius of macropores affect the spectral characteristics of the photonic crystal [8]. Macroporous silicon is used as gas sensors. The gas sensor is built on the basis of a photonic crystal, which is a narrow filter in the infrared range. A gas sensor based on macroporous silicon has wide operating ranges, compact dimensions, optical stability, and long-term stability [9]. Porous silicon with through pores is used as a membrane. An analysis of the development, advantages and disadvantages of porous silicon membranes is presented in [10]. The relaxation oscillator is made on the basis of macroporous silicon, the surface of which pores are covered with TiO_2. The oscillator combines the dielectric characteristics of TiO_2 and the characteristics of the tunnel diode, which the heterostructure has [11]. The kinetics of excess charge carriers in bilateral macroporous silicon is calculated from the system of equations. The system of equations contains diffusion equations, boundary and initial conditions. The distribution of the excess minority carrier concentration changes according to the exponential law due to a time greater than the effective life time of the charge noses [12]. A diffusion model of photoconductivity in bilateral macroporous silicon was developed. The general solution of the diffusion equation under stationary conditions and the boundary condition written on the boundaries of the macroporous silicon layers were used to calculate the photoconductivity. The dependence of photoconductivity on the minority carrier lifetime and the pore depth increases if the pore depth decreases and the lifetime increases [13]. The kinetics of photoconductivity in bilateral macroporous silicon was calculated by the finite difference method. The initial condition was stationary photoconductivity excited by light with wavelengths of 0.95 μm and 1.05 μm. On a semi-logarithmic scale, the photoconductivity changes its slope when the pore depth exceeds 250 μm [14]. The photoconductivity relaxation time in macroporous silicon is calculated from the system of

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two transcendental equations derived analytically. A layer of macroporous silicon is considered as an effective medium. The photoconductivity relaxation time decreases when the pore depth increases from 0 to 25 μm [15]. The effective lifetime of minor charge carriers for macroporous silicon with through-pores is calculated from a model that takes into account the morphology of the pores and the surface recombination velocity [16].

2. CALCULATION METHOD

Let an unpolarized electromagnetic wave be incident perpendicular to the surface of macroporous silicon. The surface of macroporous silicon on which an electromagnetic wave is incident will be called the front surface of a sample of macroporous silicon or simply the front surface. The opposite surface of macroporous silicon, through which the electromagnetic wave will pass, we will call the back surface of macroporous silicon or simply the back surface. We choose the origin of the x axis on the front surface of macroporous silicon, and the direction of the x axis is perpendicular to this surface. Let a perpendicularly incident electromagnetic wave with intensity I_0 pass through the boundary separating the air and the effective medium of macroporous silicon. Macroporous silicon is an effective medium if its bulk structural elements are much larger than the wavelength. The surface of macroporous silicon is structured. A structured surface scatters electromagnetic waves if there are structures on its surface much larger than the wavelength. Consider the case when macroporous silicon is an effective medium and its structured surface scatters light. Scattering by the surface of macroporous silicon is taken into account using the effective scattering angle β_{eff}. The x axis is placed perpendicular to the surface of the sample. The optical path travelled by an electromagnetic wave scattered at an effective angle β_{eff} is equal to $x/\cos(\beta_{eff})$. The effective absorption coefficient is equal to $\alpha(1-P)$, where α is the absorption coefficient in silicon. The intensity of the reflected electromagnetic wave $R_{0^*}I_0$, where R_{0^*} is the reflection coefficient from the surface separating air and macroporous silicon. The intensity of the refracted electromagnetic wave $(1-R_{0^*})I_0$. The electromagnetic wave refracted by the front surface will be absorbed in silicon, therefore the distribution of the intensity of the electromagnetic wave along the x-axis:

$$I_{\mathrm{Si}0}(x)=I_0\left(1-R_{0^*}\right)\exp\left(-\frac{\alpha x(1-P)}{\cos(\beta_{eff})}\right). \qquad (2.1)$$

The refracted electromagnetic wave, having passed macroporous silicon, will be reflected and refracted on the back surface. An electromagnetic wave propagating in macroporous silicon will be reflected from all its surfaces, losing its intensity due to absorption in silicon and refraction on all surfaces. An electromagnetic wave that emerges from macroporous silicon through the front, back, and side surfaces will add intensity to the reflection and transmission coefficients. Thus, multiple reflection and refraction of an electromagnetic wave on the surfaces of macroporous silicon will lead to the fact that the reflection coefficients, transmission and intensity change in macroporous silicon will be sums. The electromagnetic wave, which is described by expression (2.1), will be refracted by the back surface, so expression (2.1) must be multiplied by the transmission coefficient, which we wrote as $1-R_0$, and by the value of the exponent at a distance h, that is, by the expression $\exp(-\alpha h(1-P)/\cos(\beta_{eff}))$. The first term of the transmission coefficient through macroporous silicon with through pores is written as follows:

$$T_{Si1}=\left(1-R_{0^*}\right)\left(1-R_0\right)\exp\left(-\frac{\alpha h(1-P)}{\cos(\beta_{eff})}\right), \qquad (2.2)$$

where R_0 is the reflection coefficient from the surface separating macroporous silicon and air. The electromagnetic wave, which was first reflected from the back surface (macroporous silicon-air interface), will propagate to the front surface with an intensity written as:

$$I_{\mathrm{Si}1}(x)=I_0R_0\left(1-R_{0^*}\right)\exp\left(-\frac{\alpha(2h-x)(1-P)}{\cos(\beta_{eff})}\right). \qquad (2.3)$$

It can be seen from expression (2.3) that the incident electromagnetic wave once passed through the front surface and was reflected once from the back surface, as evidenced by the degrees of reflection and transmission coefficients. We put the expression $(2h-x)(1-P)/\cos(\beta_{eff})$ under the exponent because the origin of the coordinate system is chosen on the front surface. The electromagnetic wave reflected from the back surface of the macroporous silicon-air will be broken by the front surface of the air-silicon and exit the macroporous silicon, which will add intensity to the reflected electromagnetic wave. The electromagnetic wave described by expression (2.3) will be refracted by the front surface, so expression (2.3) must be multiplied by the transmission coefficient, which we wrote down as $1-R_0$, and by the expression $exp(-2\alpha h\times(1-P)/\cos(\beta_{eff}))$, since on the front surface $x=0$. Thus, the first term in the reflection coefficient from macroporous silicon with through pores will be the expression:

$$R_{\mathrm{Si}1}=R_0\left(1-R_0\right)\left(1-R_{0^*}\right)\exp\left(-\frac{2\alpha h(1-P)}{\cos(\beta_{eff})}\right). \qquad (2.4)$$

In addition, do not forget that the electromagnetic wave was reflected from the front surface of macroporous silicon, we will call this the zero term. It can be seen from expression (2.4) that the electromagnetic wave travelled an optical path equal to $2h/\cos(\beta_{eff})$, was reflected once, and passed through the front surface of macroporous silicon twice. The electromagnetic wave, which is reflected a second time from the front surface of macroporous silicon, will propagate to the back surface with the intensity:

$$I_{\mathrm{Si}2}(x)=I_0R_0^2\left(1-R_{0^*}\right)\exp\left(-\frac{\alpha(2h+x)(1-P)}{\cos(\beta_{eff})}\right). \qquad (2.5)$$

The electromagnetic wave described by expression (2.5) will be refracted by the back surface, so expression

(2.3) must be multiplied by the transmission coefficient, which we wrote down as $1 - R_0$, and by the expression $\exp(-\alpha(2h + h)(1 - P)/\cos(\beta_{eff}))$, since on the back surface $x = h$. The second term of the transmission coefficient through macroporous silicon with through pores will be written as:

$$T_{\mathrm{Si}2} = R_0^2(1-R_0)(1-R_{0*})\exp\left(-\frac{3\alpha h(1-P)}{\cos(\beta_{eff})}\right). \quad (2.6)$$

Let's compare expressions (2.2) and (2.6), which specify the first and second terms of the transmission coefficient through macroporous silicon. We see that in order for an electromagnetic wave to pass through macroporous silicon again, it must be reflected twice inside macroporous silicon from its surfaces and additionally pass an optical path equal to $2h/\cos(\beta_{eff})$. The electromagnetic wave, which will be reflected three times from the macroporous silicon-air interface, will propagate to the front surface with the intensity:

$$I_{\mathrm{Si}3}(x) = (1-R_{0*})R_0^3 I_0 \exp\left(-\frac{\alpha(4h-x)(1-P)}{\cos(\beta_{eff})}\right). \quad (2.7)$$

The electromagnetic wave described by expression (2.7) will be refracted by the front surface, so expression (2.7) must be multiplied by the transmission coefficient $1 - R_0$ and by the expression $\exp(-4\alpha h \times (1 - P)/\cos(\beta_{eff}))$, since on the front surface $x = 0$. The second term of the reflection coefficient from macroporous silicon:

$$R_{Si2} = R_0^3(1-R_0)(1-R_{0*})\exp\left(-\frac{4\alpha h(1-P)}{\cos(\beta_{eff})}\right). \quad (2.8)$$

To understand the general formula for the distribution of electromagnetic wave intensity in macroporous silicon, we will find the following sums:

$$I_{\mathrm{Si}1}(x) + I_{\mathrm{Si}2}(x) = I_0 R_0 \exp\left(-\frac{2\alpha h(1-P)}{\cos(\beta_{eff})}\right)(1-R_{0*}) \times$$

$$\times\left(\exp\left(\frac{\alpha x(1-P)}{\cos(\beta_{eff})}\right) + R_0\exp\left(-\frac{\alpha x(1-P)}{\cos(\beta_{eff})}\right)\right), \quad (2.9)$$

$$I_{\mathrm{Si}3}(x) + I_{\mathrm{Si}4}(x) = I_0 R_0^3 \exp\left(-\frac{4\alpha h(1-P)}{\cos(\beta_{eff})}\right)(1-R_{0*}) \times$$

$$\times\left(\exp\left(\frac{\alpha x(1-P)}{\cos(\beta_{eff})}\right) + R_0\exp\left(-\frac{\alpha x(1-P)}{\cos(\beta_{eff})}\right)\right). \quad (2.10)$$

The sums of electromagnetic wave intensities in macroporous silicon (2.9) and (2.10) can be continued by writing down the general formula:

$$I_{\mathrm{Si},2n-1}(x) + I_{\mathrm{Si},2n}(x) = I_0(1-R_{0*})\exp\left(-\frac{2\alpha nh(1-P)}{\cos(\beta_{eff})}\right) \times$$

$$\times R_0^{2n-1}\left(\exp\left(\frac{\alpha x(1-P)}{\cos(\beta_{eff})}\right) + R_0\exp\left(-\frac{\alpha x(1-P)}{\cos(\beta_{eff})}\right)\right). \quad (2.11)$$

Using expressions (2.1) and (2.11), we write down the distribution of electromagnetic wave intensity in a macroporous silicon plate with through pores:

$$I_{\mathrm{Si}}(x) = I_0(1-R_{0*})\exp\left(-\frac{\alpha x(1-P)}{\cos(\beta_{eff})}\right)\left(1 + \left(R_0 + \right.\right.$$

$$\left.\left. + \exp\left(\frac{2\alpha x(1-P)}{\cos(\beta_{eff})}\right)\right)\sum_{n=1}^{\infty}\left(R_0^{2n-1}\exp\left(\frac{2\alpha nh(1-P)}{-\cos(\beta_{eff})}\right)\right)\right). \quad (2.12)$$

Let us analyze the expressions for the first and second terms of the reflection coefficient from macroporous silicon with through-pores (2.4), (2.8) and the coefficient of origin due to macroporous silicon with through-pores (2.2), (2.6). We see that each subsequent term of the reflection coefficient from macroporous silicon and the transmission coefficient through macroporous silicon is obtained by multiplying the previous term by the expression $\exp(-2\alpha h \times (1 - P)/\cos(\beta_{eff}))$. From the above, we write down the expression for the reflection coefficient from a plate of macroporous silicon with through pores:

$$R_{Si} = R_{0*} + (1-R_0)(1-R_{0*}) \times$$

$$\times\sum_{n=1}^{\infty}\left(R_0^{\,2n-1}\exp\left(-\frac{2\alpha nh(1-P)}{\cos(\beta_{eff})}\right)\right). \quad (2.13)$$

The transmission coefficient through a plate of macroporous silicon with through pores:

$$T_{Si} = (1-R_0)(1-R_{0*}) \times$$

$$\times\sum_{n=1}^{\infty}\left(R_0^{\,2n-2}\exp\left(-\frac{\alpha h(2n-1)(1-P)}{\cos(\beta_{eff})}\right)\right). \quad (2.14)$$

From formulas (2.13) and (2.14), we express the ratio between the coefficients of reflection and transmission of an electromagnetic wave through macroporous silicon with through pores:

$$T_{\mathrm{Si}} = \frac{R_0^{-1}(R_{si}-R_0)}{\exp\left(-\frac{\alpha h(1-P)}{\cos(\beta_{eff})}\right)} = \left(\frac{R_{si}}{R_0} - 1\right)\exp\left(\frac{\alpha h(1-P)}{\cos(\beta_{eff})}\right). \quad (2.15)$$

The product under the sign of the infinite sum in the expressions (2.12), (2.13), (2.14) is always less than the unit $R_{02}\cdot exp(-2\alpha h(1 - P)/\cos(\beta_{eff})) < 1$, because each of these multipliers is less than unit $R_{02} < 1$ and $exp(-2\alpha h(1- P)/\cos(\beta_{eff})) < 1$. We denote by $\alpha = R_{02}\cdot exp(-2\alpha h(1 - P)/\cos(\beta_{eff})) < 1$ in order to apply to expressions (2.12), (2.13) and (2.14) the relation:

$$\sum_{n=0}^{\infty}(a^n) \to \left|\begin{array}{l}\dfrac{1}{1-a}\ \ if\ \ |a|<1 \\ \infty \text{ if } a \geq 1\end{array}\right., \quad (2.16)$$

The sums in expressions (2.12), (2.13), (2.14) start with one, so let's introduce the substitution $k = n - 1$, that is $n = k + 1$, and move on to the sums starting from zero. The infinite sum from (2.13) using the substitution $k = n - 1$ and (2.16) can be written as follows:

$$\sum_{n=1}^{\infty}\left(R_0^{2n-1}\exp\left(-\frac{2\alpha nh(1-P)}{\cos(\beta_{eff})}\right)\right)=$$

$$=\sum_{k=0}^{\infty}\left(R_0^{2k+1}\exp\left(-\frac{2\alpha h(k+1)(1-P)}{\cos(\beta_{eff})}\right)\right)=$$

$$=R_0\exp\left(-\frac{2\alpha h(1-P)}{\cos(\beta_{eff})}\right)\sum_{k=0}^{\infty}\left(R_0^2\exp\left(-\frac{2\alpha h(1-P)}{\cos(\beta_{eff})}\right)^k\right)=$$

$$=\frac{R_0\exp(-2\alpha h\cos^{-1}(\beta_{eff})(1-P))}{1-R_0^2\exp(-2\alpha h\cos^{-1}(\beta_{eff})(1-P))}. \quad (2.17)$$

The reflection coefficient of an electromagnetic wave from a plate of macroporous silicon with through pores will be written as:

$$R_{Si}=R_{0*}+R_0(1-R_0)(1-R_{0*})\times$$

$$\times\frac{\exp(-2\alpha h\cos^{-1}(\beta_{eff})(1-P))}{1-R_0^2\exp(-2\alpha h\cos^{-1}(\beta_{eff})(1-P))}=$$

$$=R_{0*}+\frac{R_0(1-R_0)(1-R_{0*})}{\exp(2\alpha h\cos^{-1}(\beta_{eff})(1-P))-R_0^2}. \quad (2.18)$$

The infinite sum from (2.14) using (2.16) can be written as follows:

$$\sum_{n=1}^{\infty}(R_0^{2n-2}\exp(-\alpha h(2n-1)\cos^{-1}(\beta_{eff})(1-P))=$$

$$=\sum_{k=0}^{\infty}(R_0^{2k}\exp(-\alpha h(2k+1)\cos^{-1}(\beta_{eff})(1-P))=$$

$$=\exp(-\frac{\alpha h(1-P)}{\cos(\beta_{eff})})\sum_{k=0}^{\infty}(R_0^2\exp(-\frac{2\alpha h(1-P)}{\cos(\beta_{eff})}))^k=$$

$$=\frac{\exp(-\alpha h\cos^{-1}(\beta_{eff})(1-P))}{1-R_0^2\exp(-2\alpha h\cos^{-1}(\beta_{eff})(1-P))}. \quad (2.19)$$

Then, the transmission coefficient of an electromagnetic wave through a plate of macroporous silicon with through pores will be written as:

$$T_{Si}=\frac{(1-R_0)(1-R_{0*})\exp(-\alpha h\cos^{-1}(\beta_{eff})(1-P))}{1-R_0^2\exp(-2\alpha h\cos^{-1}(\beta_{eff})(1-P))}=$$

$$=\frac{(1-R_0)(1-R_{0*})\exp(\alpha h\cos^{-1}(\beta_{eff})(1-P))}{\exp(2\alpha h\cos^{-1}(\beta_{eff})(1-P))-R_0^2}. \quad (2.20)$$

The distribution of the intensity of the electromagnetic wave in a plate of macroporous silicon with through pores, based on expressions (2.12) and (2.16), will be written as follows:

$$I_{\mathrm{Si}}(x)=I_0(1-R_{0*})\exp\left(-\frac{\alpha x(1-P)}{\cos(\beta_{eff})}\right)\times$$

$$\times\left(1+\frac{R_0(R_0+\exp(2\alpha x\cos^{-1}(\beta_{eff})(1-P)))}{\exp(2\alpha h\cos^{-1}(\beta_{eff})(1-P))-R_0^2}\right), \quad (2.21)$$

or:

$$I_{\mathrm{Si}}(x)=I_0(1-R_{0*})\left(\frac{\exp(-\alpha x\cos^{-1}(\beta_{eff})(1-P))}{1-R_0^2\exp(-2\alpha h\cos^{-1}(\beta_{eff})(1-P))}+\right.$$

$$\left.+\frac{R_0\exp(-\alpha(2h-x)\cos^{-1}(\beta_{eff})(1-P))}{1-R_0^2\exp(-2\alpha h\cos^{-1}(\beta_{eff})(1-P))}\right). \quad (2.22)$$

The adsorption coefficient depends on the reflection coefficient from the front surface, the reflection coefficient from the internal interface of macroporous silicon - air, and the thickness of the sample. The absorption coefficient of an electromagnetic wave for a macroporous silicon wafer with through pores is found through the reflection and transmission coefficients:

$$A_{\mathrm{Si}}=1-(R_{\mathrm{Si}}+T_{\mathrm{Si}})=1-R_{0*}-\left(R_0+\exp\left(\frac{\alpha h(1-P)}{\cos(\beta_{eff})}\right)\right)\times$$

$$\times\frac{(1-R_0)(1-R_{0*})\exp(-2\alpha h\cos^{-1}(\beta_{eff})(1-P))}{1-R_0^2\exp(-2\alpha h\cos^{-1}(\beta_{eff})(1-P))}=$$

$$=(1-R_{0*})\left(1-\left(\left(\left(R_0\exp(-\frac{\alpha h(1-P)}{\cos(\beta_{eff})}\right)+1\right)\right)\times\right.$$

$$\left.\times\frac{(1-R_0)\exp(-\alpha h\cos^{-1}(\beta_{eff})(1-P))}{1-\left(R_0\exp(-\alpha h\cos^{-1}(\beta_{eff})(1-P))\right)^2}\right)=$$

$$=\frac{(1-R_0)(1-\exp(-\alpha h\cos^{-1}(\beta_{eff})(1-P)))}{1-R_0\exp(-\alpha h\cos^{-1}(\beta_{eff})(1-P))}. \quad (2.23)$$

The adsorption coefficient expressed in terms of the reflection coefficients from the surface of macroporous silicon and the plate of macroporous silicon with through pores is written as:

$$A_{\mathrm{Si}}=1-R_{0*}-R_{\mathrm{Si}}\left(R_0+\exp\left(\frac{\alpha h(1-P)}{\cos(\beta_{eff})}\right)\right). \quad (2.24)$$

The adsorption coefficient depends on the reflection coefficient from the front surface, the reflection coefficient from the macroporous silicon plate with through pores and the reflection coefficient from the internal interface of macroporous silicon - air.

3. RESULTS AND DISCUSSION

Consider Consider macroporous silicon with through-pores with a thickness of 50 μm. Macroporous silicon with through pores is obtained from macroporous silicon on a single crystal substrate by increasing the pore diameter of the pores at the maximum depth to their intersection. It separates after gluing to the base [16]. Macroporous silicon with through-pores with a thickness more than 50 μm can be obtained if the underlying substrate is removed by etching [10]. Such macroporous silicon with through pores is supported on the substrate from the sides.

Fig. 1 shows the distribution of electromagnetic wave intensity in macroporous silicon with through-pores with different volume fraction of pores calculated from expression (2.22). An electromagnetic wave with a wavelength of 0.95 μm falls on the surface of macroporous silicon. Macroporous silicon with through pores will be considered an effective medium, that is, the size of the pores and the distance between them is smaller than the length of the electromagnetic wave that falls on the surface of the sample. Curve 1 shows the distribution of electromagnetic wave intensity in a single crystal of silicon with a thickness of 50 μm. The distribution takes into account the reflection and transmission of internal surfaces. Curve 2 shows that the distribution of the intensity of the electromagnetic wave in macroporous silicon increases in comparison with the distribution of the intensity in a single crystal of silicon.

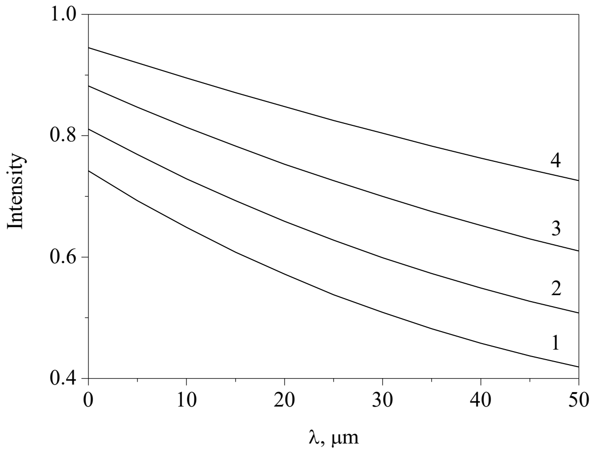

Fig. 1 – Distribution of electromagnetic wave intensity in macroporous silicon with through pores with a volume fraction of pores: 1–0; 2–0.2; 3–0.4; 4–0.6

This is due to an increase in transmission through the front surface of macroporous silicon and an increase in reflection from the inner side of the back surface. The increase in intensity of the electromagnetic wave near the back surface is greater than the increase in intensity near the front surface. The increase in the intensity of the electromagnetic wave near the back surface increases as the volume fraction of the pores increases (see Fig. 2 – Fig. 4).

The effective absorption by the effective macropore volume is reduced by non-absorbing pores. Despite this, the absorption of the material increases, due to the better transmission of the front surface and the reflection of the front and back surfaces from the inside. Intensity calculations in macroporous silicon with through pores are made for a maximum pore volume fraction of 0.6, because it will crumble if the pore diameter is equal to the distance between the pore centers, that is, the pore volume fraction will exceed $P = \pi D_2/(4a_2) = \pi/4 = 0.78$.

Fig. 2 shows the reflection spectrum of macroporous silicon with through-pores with different volume fraction of pores calculated from expression (2.18). Curve 1 shows the reflection spectrum of a silicon single crystal plate with a thickness of 50 μm calculated according to expression (2.18) ($P = 0$). It is given to compare the reflection spectra of single crystal and macroporous silicon with through pores. The reflection spectrum of macroporous silicon with through pores up to 0.9 μm is the reflection spectrum of the air- macroporous silicon interface.

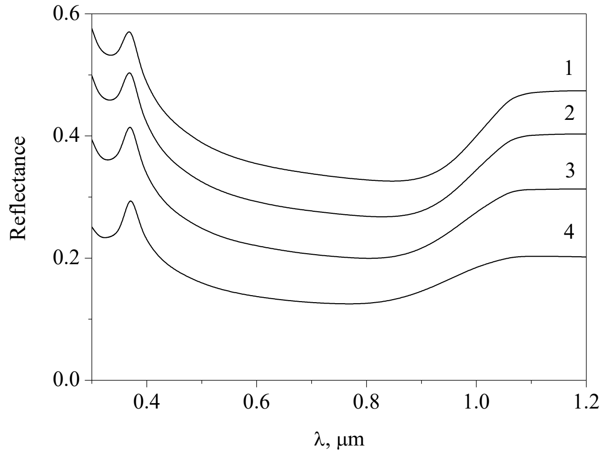

Fig. 2 – Reflectance spectrum of macroporous silicon with through pores with a volume fraction of pores: 1–0; 2–0.2; 3–0.4; 4–0.6

The spectrum of reflection from 0.9 μm to 0.2 μm is the spectrum of reflection from the front surface from the outside and inside, the back surface from the inside, and absorption by the effective medium of macroporous silicon. The increase in reflectance at a wavelength from 0.9 μm to 1.03 μm is due to the absorption of an electromagnetic wave in the volume of the sample. The reflection from the front surface decreases when the volume fraction of pores increases (see Fig. 2). The larger the volume fraction of pores, the more the reflection of macroporous silicon with through-pores decreases. The beginning of the increase in reflection of macroporous silicon with through pores is shifted from 0.9 μm to 0.8 μm due to reflection from the back surface, when the volume fraction of pores increases from 0 to 0.6.This indicates that the efficiency of absorption by the effective volume decreases due to the fact that the pore volume increases, and it does not absorb. Absorption efficiency by effective volume decreases. The transmission of the front surface increases due to the fact that the reflection of the front surface decreases, so it is necessary to consider the transmission spectrum of macroporous silicon with through pores.

Fig. 3 shows the transmission spectrum of macroporous silicon with through-pores with different volume fraction of pores calculated from expression (2.20). Curve 1 shows the transmission spectrum of a single crystal silicon plate with a thickness of 50 μm. The beginning of the transmission spectrum of macroporous silicon with through-pores shifts from 0.8 μm to 0.65 μm, as the volume fraction of pores increases from 0 to 0.6. This indicates that the efficiency of absorption by the effective volume decreases due to the fact that the volume fraction of pores increases. The transmittance of macroporous silicon with through-pores increases as the volume fraction of pores increases (see Fig. 2). The greater the volume fraction of pores, the greater the transmittance of macroporous silicon with through-pores increases (see Fig. 3). The transmittance of macroporous silicon with through-pores increases due to the reduction of reflection by the front surface. The effective volume (the presence of non-absorbing volume) and the increase in transmittance of the back surface reduce the efficiency of electromagnetic wave absorption by macroporous through-pore silicon.

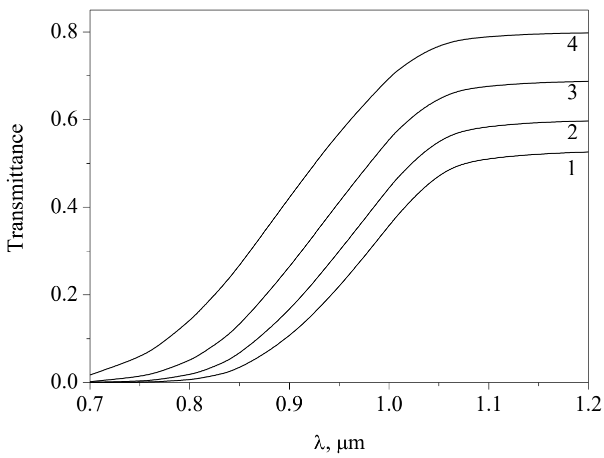

Fig. 3 – Transmittance spectrum of macroporous silicon with through pores with a volume fraction of pores: 1–0; 2–0.2; 3–0.4; 4–0.6

Fig. 4 shows the absorption spectrum of macroporous silicon with through-pores with different volume fraction of pores calculated from expression (2.23). Curve 1 shows the calculated absorption spectrum of a single crystal silicon plate with a thickness of 50 μm. The absorption spectrum of macroporous silicon with through pores increases in intensity, and the long-wavelength limit of the absorption spectrum shifts from 1.08 μm to 1.03 μm when the volume fraction of pores increases from 0 to 0.6. The increase in absorption occurs due to the decrease in reflection from the frontal surface (see Fig. 2, Fig. 4). A decrease in reflection means an increase in transmission for all surfaces: front, rear and sides, but for electromagnetic waves with a high absorption coefficient, this does not matter because they will be absorbed.

These electromagnetic waves will be partially reflected from the internal side of the rear surface, which will increase both absorption and transmission of macroporous silicon with through pores (see Fig. 3, Fig. 4). At the same time, the absorption of the effective volume decreases due to the increase in non-absorbing voids (pores), with an increase in the volume fraction of pores. Non-absorbent voids (pores) reduce the effective absorption rate by the effective volume. Thus, the effective surface increases the absorption and the effective volume reduces the absorption of the electromagnetic wave as the pore volume fraction increases.

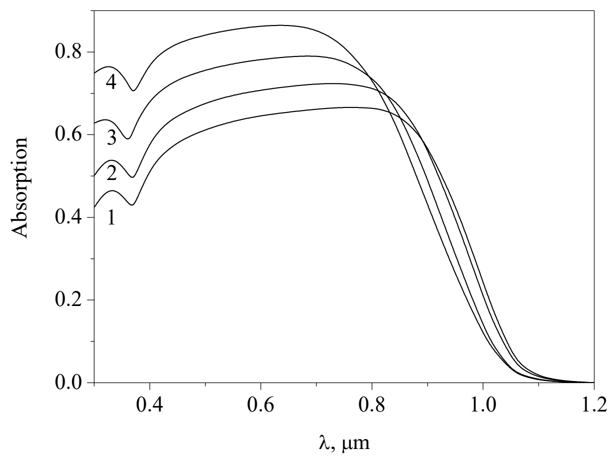

Fig. 4 – Absorption spectrum of macroporous silicon with through pores with a volume fraction of pores: 1–0; 2–0.2; 3–0.4; 4–0.6

Fig. 5 shows the reflection, transmission and absorption spectra of macroporous silicon with through pores with different sample thicknesses. The difference in the reflection spectra of macroporous silicon with through-pores with a sample thickness of 50 μm and 100 μm is observed at electromagnetic wavelengths from 0.8 μm to 1.1 μm.

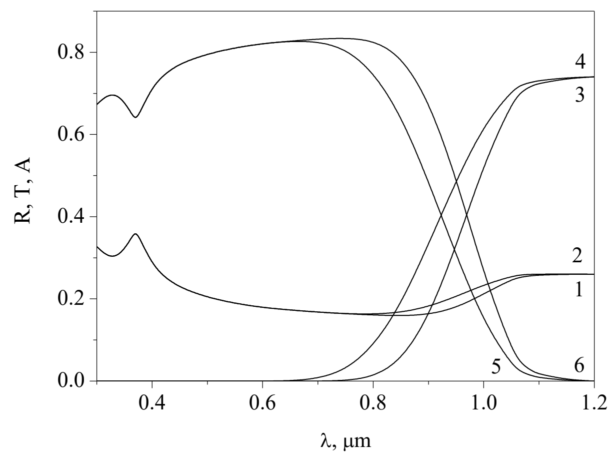

Fig. 5 – Spectra of reflectance (curves 1, 2), transmission (curves 3, 4), absorption (curves 5, 6) of macroporous silicon with through-pores with sample thickness, μm: 1, 3, 5–50; 2, 4, 6–100

The reflection spectra coincide for wavelengths from 0.3 μm to 0.8 μm and from 1.02 μm to 1.2 μm (see Fig. 5 curves 3, 4). Electromagnetic waves with these wavelengths are either completely absorbed by macroporous silicon or not at all. If the penetration depth of the electromagnetic wave into the effective medium of macroporous silicon is greater than its thickness, then the electromagnetic wave will pass through the sample and increase transmittance. If the penetration depth is greater than two thicknesses of the sample, then the electromagnetic wave will be partially reflected from the back surface, pass through the sample, partially pass through the front surface and increase the reflection. That is, macroporous silicon with through pores does not completely absorb electromagnetic waves whose penetration depth is greater than the thickness of the sample. The thinner the sample, the fewer photons it will absorb. Electromagnetic waves that are not completely absorbed will increase transmission and absorption.

4. CONCLUSIONS

The reflection of macroporous silicon with through-pores decreases as the volume fraction of pores increases. This is due to the reduction of the difference between the refractive indices of air and the effective medium. The reflection of the inner side of the back surface decreases with increasing pore volume fraction, so the reflection of macroporous silicon with through pores further decreases for electromagnetic wave lengths from 0.9 μm to 1.3 μm.

The transmittance of macroporous silicon with through-pores increases due to the reduction of reflection by the front and back surfaces and the reduction of absorption by the volume of the effective medium with an increase in the volume fraction of the pores. That is, the surfaces of macroporous silicon with through-pores and its effective volume become more transparent as the volume fraction of pores increases. Macroporous silicon with through pores becomes more transparent as its thickness decreases.

Absorption of electromagnetic radiation by macroporous silicon with through-pores increases with an increase in the volume fraction of pores. This is due to the fact that the reflection of macroporous silicon with through-pores decreases with an increase in the volume fraction of pores. The effective volume (the presence of non-absorbing volume) and the increase in transmittance of the back surface decrease the efficiency of electromagnetic wave absorption by macroporous silicon with through-pores with increasing pore volume fraction.

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Оптика макропористого кремнію з наскрізними порами

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В роботі представлена теорія та розрахунок попускання, відбиття та поглинання макропористого кремнію з наскрізними порами. Макропористого кремнію з наскрізними порами розглянутий як ефективне середовище, поверхня якого розсіює електромагнітні хвилі. Розсіювання поверхнею макропористого кремнію враховується використанням ефективного кута розсіювання. Ефективний комплексний показник заломлення та ефективний коефіцієнт поглинання розраховуються за формулами змішування. Виведені аналітичні формули для розрахунку пропускання, відбиття та поглинання макропористого кремнію з наскрізними порами враховують численні відбиття від внутрішніх сторін передньої та задньої поверхонь. Проаналізований вплив об’ємної частки пор та товщини макропористого кремнію з наскрізними порами на його відбиття, пропускання та поглинання. Відбиття та пропускання фронтальної та тильної поверхонь та поглинання ефективним об’ємом макропористого кремнію залежать від об’ємної частки пор та впливають на оптичні властивості макропористого кремнію з наскрізними порами.

Ключові слова: Макропористий кремній, Наскрізні пори, Відбиття, Поглинання, Пропускання.