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Reflection of Macroporous Silicon, Nanowires, and a Two-layer Structure of Silicon with an Effective Medium

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A theoretical model of reflection of macroporous silicon and arrays of silicon nanowires on a monocrystalline substrate is presented. Macroporous silicon and silicon structured by nanowires are considered as a two-layer structure of silicon with an effective medium. The analytical model of the reflection from a two-layer silicon structure with an effective medium takes into account the absorption of light by the structure and the multiple reflections of light from the surfaces of the sample and the interface between the effective medium and the monocrystalline substrate. The reflection coefficient from a structured surface, which is the boundary between two media, contains the complex index of refraction of silicon. The effective index of refraction of the effective medium is found from the expression for mixing two media. The reflection of light falling on flat surfaces at different angles is calculated according to Fresnel's formulas. The frontal structured surface and the second structured surface were considered as Lambert surfaces. Total internal reflection from a flat surface between silicon and air is given by Snelius' law, and from structured surfaces between silicon and the effective medium and between the effective medium and air is accounted for by coefficients. The reflection spectra from macroporous silicon and arrays of silicon nanowires on a monocrystalline substrate are calculated according to analytically derived formulas. It is shown that the magnitude of reflection spectra from macroporous silicon and arrays of silicon nanowires on a monocrystalline substrate decreases when the volume fraction of pores increases. The reflectance begins to increase again when the pore volume fraction is high. Reflection from the surface between the effective medium and air is observed at a high volume fraction of pores.

Keywords: Macroporous silicon, Black silicon, Nanowires, Reflectance coefficient, Reflectance spectrum.

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1. INTRODUCTION

Two-dimensional structures of macroporous silicon absorb light better than silicon single crystal due to the pores. The optical properties of the quasi-periodic structure of macroporous silicon have been studied. The structure of macroporous silicon consisted of periodically arranged grooves with macropores. The combined structure has polarization selectivity and is the basis of a thermal photodetector [1]. The IR absorption spectra were studied in a two-dimensional structure of macroporous silicon with a microporous silicon layer on the surface of the pores. The IR absorption spectra of light in 2D structures of macroporous silicon with a surface nanocoating contain oscillations [2]. Oscillations in the IR region of the spectrum are observed in macroporous silicon with a SiO_2 layer deposited on the sample surface. The oscillations are explained by the electro-optical Wannier-Stark effect [3]. The optical properties of the anti-reflection coating of n and p-type macroporous silicon obtained by electrochemical etching show a reflectance below 1 % in the visible region of the electromagnetic spectrum. The porosity and thickness of the macroporous layer are specified by the etching conditions [4]. The etching conditions of macroporous silicon change its surface structure and optical properties. Extended alkaline etching of macroporous silicon improves light capture by the surface of arrays of sharp nanospikes [5]. The duration of the etching optimizes the structured surface for maximum absorption of incident light. A passivating layer of TiO2 with a thickness of 40 nm effectively protects the macroporous layer from external action and surface degradation [6]. Black silicon based on porous silicon on a monocrystalline silicon substrate is considered as a two-layer medium with an effective medium. The optical properties of black silicon are calculated within the effective medium approximation. Black silicon based on porous silicon has a low reflectivity in the visible range, so it is used in solar cells [7]. The energy efficiency of solar panels is carried out using a control and monitoring system. The combined data is obtained as a result of the operation of the system. They are used to optimize the area of solar cells and predict the amount of energy produced by a solar cell [8]. Experiment and simulation proved the efficiency of the developed system of LED modules and solar panels [9]. The distribution of excess charge carriers in bilateral macroporous silicon is calculated by a numerical method from the system of equations. The pore depth of one macroporous layer was equal to 100 μm, and the other varied from zero to to 400 μm. The similarity of the distribution of charge carriers in macroporous silicon with one and two macropore layers is shown. The recombination of excess charge carriers in each porous layer and their diffusion into recombination centers determine the distribution of charge carriers in the sample [10]. The photoconductivity of bilateral macroporous silicon and macroporous silicon with through pores was calculated within the diffusion model. The bulk lifetime of minority charge carriers and

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the pore depth of each macroporous layer determine the photoconductivity of bilateral macroporous silicon. The photoconductivity of macroporous silicon with through pores is determined by the surface recombination velocity on the surface of pores of macroporous layers [11]. Macroporous silicon with a pore depth of 9 μm is passivated by AlOx and thus provides a carrier lifetime of 2 ms, which corresponds to a surface recombination velocity of 0.08 m/s. This structure of macroporous silicon has a reflection coefficient of 1.5 % [12]. The formula for determining the photoconductivity relaxation time in macroporous silicon was derived analytically. The photoconductivity relaxation time depends on the geometric parameters of the macroporous layer (pore diameter, distance between pore centers, layer thickness), the surface recombination velocity, and bulk minority-carrier lifetime [13]. The kinetics of distribution of the excess minority carrier concentration in bilateral macroporous silicon with a pore depth of 100 μm and 200 μm was calculated by the finite difference method. A high concentration of charge carriers is observed in the frontal porous layer; it quickly decreases due to the rapid recombination of charge carriers on the pore surface [14]. The photoconductivity kinetics of bilateral macroporous silicon was calculated by the finite difference method. The non-exponential part of photoconductivity decay increases as the pore depth increases. On a semilogarithmic scale, the exponential decay of photoconductivity changes its incline when the pore depth is more than 250 μm [15]. Light reflection by macroporous silicon is used to calculate the distribution of charge carriers, photoconductivity and their kinetics. The purpose of this work is to calculate and study the absorption coefficient of macroporous silicon with macropores or nanowires in the effective medium approximation. The work will be useful for developers of solar cells and antireflection coatings.

2. REFLECTION COEFFICIENT OF MACROPOROUS SILICON, NANOWIRES, AND A TWO-LAYER STRUCTURE OF SILICON WITH AN EFFECTIVE MEDIUM

Fig. 1 shows the structure of macroporous silicon, which consists of a layer of macroporous silicon with a thickness h_1 and a monocrystalline substrate with a thickness h_2. A structure with silicon pillars or nanowires will have a similar cross section. Silicon monocrystal structured with macropores, nanowires, and pyramids is called black silicon, if it strongly absorbs light, that is, it becomes black. Let us consider a layer of macroporous silicon as an effective medium. The layer of macroporous silicon is an effective medium in cases where the wavelength of light is several times greater than the size of the pores and the distance between them. In the general case, we have a two-layer silicon structure with an effective medium. The surface on which the light falls is called the frontal surface. The frontal surface is a structured surface and is both the surface of the sample and the surface of the macroporous layer. The sample has a second structured surface. The surface of the sample opposite to the frontal surface of the sample will be called the rear surface. The rear surface is a flat surface. Thus, a sample of macroporous silicon has a structured frontal surface, a second structured surface, and a flat rear surface. The structured frontal surface and the second structured surface reflect, transmit and scatter light.

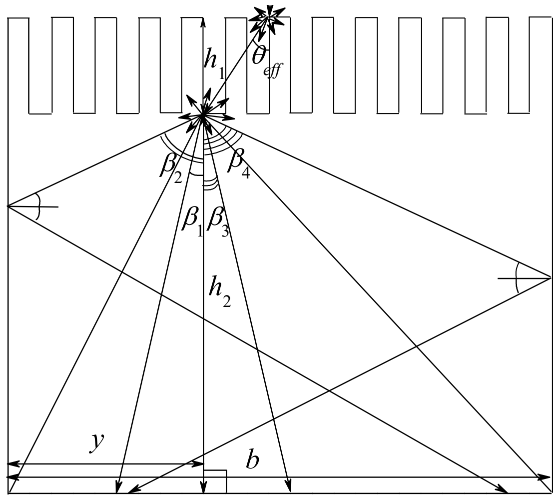

Fig. 1 – Scheme of porous silicon with macropores or nanowires

Consider reflection from a monocrystalline substrate. The monocrystalline substrate has a second structured surface that scatters light and a flat rear surface. Let light fall on the second structured surface. The side surfaces of the monocrystalline substrate are flat and perpendicular to the second structured and rear surface. The light that enters on the monocrystalline substrate through the structured surface will be scattered. Consider this structured surface as a Lambert surface. Let an element of the second structured surface emit light with intensity I_0 in the direction of the perpendicular, then the light intensity $I = I_0\cos(\beta)$ is observed on the sphere area element located at an angle from the normal. The light intensity observed on the area element of the flat rear surface is $I = I_0\cos(\beta)\sin(\beta) = I_0\sin(2\beta)/2$. Let us single out the angles: the critical angle of total internal reflection from the side surface, equal to $\pi/2 - \arcsin(1/n_{Si})$, the critical angle of total internal reflection from the flat rear surface, equal to $\arcsin(1/n_{Si})$, and the angle separating the side and flat rear surface equal to $\arctan(y/h_2)$ (see Fig. 1). Here n_{Si} is the refractive index of the silicon single crystal. The angle β_1 is equal to the critical angle of total internal reflection if it is less than the angle separating the side and rear surfaces. Otherwise, the angle β_1 is equal to the angle separating the side and rear surfaces:

$$\beta_1(y) = \left| \begin{array}{l} \arcsin\left(\dfrac{1}{n_{Si}}\right), \text{ if } \arcsin\left(\dfrac{1}{n_{Si}}\right) < \arctan\left(\dfrac{y}{h_2}\right) \\ \arctan\left(\dfrac{y}{h_2}\right), \text{ in other cases} \end{array} \right. . \quad (2.1)$$

The angle β_2 is equal to the angle separating the side and rear surfaces or the critical angle of total internal reflection from the side surface, if it is less than the critical angle of total internal reflection from the side surface. Otherwise, the angle β_2 is equal to the critical angle of total internal reflection from the side surface:

$$\beta_2(y) = \begin{vmatrix} \arctan\left(\dfrac{y}{h_2}\right), \text{ if } \arctan\left(\dfrac{y}{h_2}\right) < \dfrac{\pi}{2} - \arcsin\left(\dfrac{1}{n_{Si}}\right) \\ \dfrac{\pi}{2} - \arcsin\left(\dfrac{1}{n_{Si}}\right), \text{ in other cases} \end{vmatrix} .(2.2)$$

Angles β_3, β_4 are similar to angles β_1, β_2, only for the other side:

$$\beta_3(y) = \begin{vmatrix} \arcsin\left(\dfrac{1}{n_{Si}}\right), \text{ if } \arcsin\left(\dfrac{1}{n_{Si}}\right) < \arctan\left(\dfrac{b-y}{h_2}\right) \\ \arctan\left(\dfrac{b-y}{h_2}\right), \text{ in other cases} \end{vmatrix} ,(2.3)$$

$$\beta_4(y) = \begin{vmatrix} \arctan\left(\dfrac{b-y}{h_2}\right), \text{ if } \arctan\left(\dfrac{b-y}{h_2}\right) < \dfrac{\pi}{2} - \arcsin\left(\dfrac{1}{n_{Si}}\right) \\ \dfrac{\pi}{2} - \arcsin\left(\dfrac{1}{n_{Si}}\right), \text{ in other cases} \end{vmatrix} .(2.4)$$

To find the reflection coefficient from a monocrystalline substrate, we need to find a normalized intensity distribution of the reflected light on a flat rear surface. For convenience, we normalize the intensity distribution of light on the rear surface to the intensity of light incident on a monocrystalline substrate. Let the light pass from the structured frontal surface to the opposite flat rear surface. Let us take into account that part of the light was reflected from the flat side surfaces and the flat rear surface. The normalized intensity distribution of light transmitted through a monocrystalline substrate and reflected from the opposite surface is written as:

$$\begin{aligned} I_{SR3}(h_2,y) = \frac{1}{2}\Bigg(& \int_0^{\beta 1(y)} R(\beta)\sin(2\beta)\exp(-\frac{\alpha h_2}{\cos(\beta)})d\beta + \\ & + \int_0^{\beta 3(y)} R(\beta)\sin(2\beta)\exp(-\frac{\alpha h_2}{\cos(\beta)})d\beta + \\ & + \int_{\beta 1(y)}^{\beta 2(y)} \sin(2\beta)\exp(-\frac{\alpha h_2}{\cos(\beta)})d\beta + \\ & + \int_{\beta 3(y)}^{\beta 4(y)} \sin(2\beta)\exp(-\frac{\alpha h_2}{\cos(\beta)})d\beta + \\ & + \int_{\beta 2(y)}^{\pi/2} R(\beta)^{kr(\beta)}\sin(2\beta)\exp(-\frac{\alpha h_2}{\cos(\beta)})d\beta + \\ & + \int_{\beta 4(y)}^{\pi/2} R(\beta)^{kr(\beta)}\sin(2\beta)\exp(-\frac{\alpha h_2}{\cos(\beta)})d\beta \Bigg), \quad (2.5) \end{aligned}$$

where $R(\beta)$ is the reflection coefficient from a flat surface, calculated using the Fresnel formula. If we have a flat surface, then: $I_{SR3}(h_2,y) = R(0)\exp(-2\alpha h_2)$. Let us explain expression (2.5). The first two terms in expression (2.5) show the intensity of the reflected light incident on a flat rear surface at angles less than the critical angle of total internal reflection. These two integrals contain the silicon-air plane reflection coefficient, which depends on the angle of incidence, so it is under the integral. The next two terms show the intensity of the reflected light, which was incident from the second structured surface onto the flat rear surface at angles greater than the critical angle of total internal reflection, but less than the critical angle of total internal reflection counted from the flat side surface. A reflected light incident at angles greater than the critical angle of total internal reflection is reflected completely from a flat surface. The next two terms show the intensity of the reflected light, which was incident from the second structured surface onto the flat rear surface at angles greater than the critical angle of total internal reflection, but less than the critical angle of total internal reflection counted from the flat side surface. A reflected light incident at angles greater than the critical angle of total internal reflection is reflected completely from a flat surface. The last two terms take into account the reflection of light from the side surface. Light is reflected from a flat side surface partly due to the fact that it falls on the side flat surface at angles less than the critical angle of total internal reflection. At that, if light is partially reflected from the side surfaces, then it is completely reflected from the flat rear surface and vice versa. This is because the sum of the angles at which light falls on a flat side surface and a flat rear surface is 90 degrees (see Fig. 1). If one of the angles of incidence of light on a flat surface, such as a side surface, is less than the critical angle of total internal reflection, the other angle of incidence of light on a flat rear surface will necessarily be greater than the critical angle of total internal reflection. The angles of incidence of light are counted from the perpendiculars of their surfaces. The angles of incidence on the flat side surfaces and the flat rear surface of the monocrystalline substrate are consistent with the angles of light wave exit from the second structured surface by conditions (2.1) – (2.4).

The reflection coefficient of light from a monocrystalline substrate is the sum of the reflection coefficient from the structured surface and the sum of the coefficients that are formed due to the reflection inside the monocrystallinel substrate. The coefficient of reflection of light from the second structured surface will be the zero term of the coefficient of reflection of light from a monocrystalline substrate. Light passes through the second structured surface, is absorbed by the monocrystalline substrate, is reflected from the rear surface, absorbed again and exits through the second structured surface. The sum from zero to the first term of the distribution of the reflection coefficient from a monocrystalline substrate with a structured surface will be written as:

$$R_{m1}(y) = R_{s2*} + (1 - R_{s2*})(1 - R_{s2}) I_{SR3}(2h_2, y) , \quad (2.6)$$

where R_{s2*}, R_{s2} are the reflection coefficients from the second structured surface, when light propagates in the directions macroporous silicon – silicon and silicon – macroporous silicon, respectively. The reflection coefficient from a flat rear surface is determined by the Fresnel formulas. It depends on the angle of incidence of light; therefore it is under the integral in the normalized distribution of the intensity of the reflected wave

(2.5). Expression (2.6) contains the value $2h_2$. This means that light passes to the flat rear surface, is reflected from it according to the Fresnel law, is reflected from the side surface and returns to the second structured surface. We will write it as:

$$\cos(\beta)\exp\left(\frac{-\alpha h}{\cos(\beta)}\right)R(\beta)\exp\left(\frac{-\alpha h_2}{\cos(\beta)}\right)=$$

$$=\cos(\beta)R(\beta)\exp\left(\frac{-2\alpha h_2}{\cos(\beta)}\right). \quad (2.7)$$

Light is reflected from the second structured surface, so the intensity of light should be multiplied by the reflection coefficient from the second structured surface and by the average value of the normalized intensity distribution of the reflected wave from $2h_2$. The absorption-reflection-absorption cycle will repeat again, so you need to additionally multiply by the value of the normalized intensity distribution of the reflected wave from $2h_2$. The sum from zero to the second term in the distribution of the reflection coefficient from a monocrystalline substrate with a structured surface will be written as:

$$R_{m2}(y)=R_{s2^*}+(1-R_{s2^*})(1-R_{s2})\times$$

$$\times I_{SR3}(2h_2,y)(1+R_{s2}\bar{I}_{SR3}(2h_2)), \quad (2.8)$$

where we marked:

$$\bar{I}_{SR3}(2h_2)=\frac{1}{b}\int_0^b I_{SR3}(2h_2,y)dy. \quad (2.9)$$

We denoted the length of the sample b (see Fig. 1). Let us analyze expression (2.8). Expression (2.8) differs from expression (2.6) only by the fourth factor of the second term. The first and second factors of the second term are the transmission coefficients through the second structured surface when light propagates in the directions of macroporous silicon – silicon and silicon – macroporous silicon. Here, the transmission coefficients are expressed in terms of the reflection coefficients. The third factor of the second term is the normalized intensity distribution of the reflected wave (2.5), written for double the thickness of the monocrystalline substrate. The fourth factor of the second term of expression (2.8) contains the sum of one and the product of the normalized average intensity of light on the second structured surface and the reflection coefficient of this surface when light propagates in the direction of silicon - macroporous silicon. The sum from zero to the third term in the distribution of the reflection coefficient from a monocrystalline substrate with a structured surface will be written as:

$$R_{m3}(y)=R_{s2^*}+(1-R_{s2^*})(1-R_{s2})I_{SR3}(2h_2,y)\times$$

$$\times(1+R_{s2}\bar{I}_{SR3}(2h_2)+(R_{s2}\bar{I}_{SR3}(2h_2))^2). \quad (2.10)$$

Using expressions (2.6), (2.8) and (2.10), we write down the distribution of the reflection coefficient from a monocrystalline substrate with a structured surface:

$$R_m(y)=R_{s2^*}+(1-R_{s2^*})(1-R_{s2})\times$$

$$\times I_{SR3}(2h,y)\sum_{n=1}^{\infty}((R_{s2}\bar{I}_{SR3}(2h))^{n-1}). \quad (2.11)$$

The infinite sum in the expression (2.11) is equal to the expression that will be written as:

$$R_m(y)=R_{s^*}+\frac{(1-R_{s2^*})(1-R_{s2})I_{SR3}(2h,y)}{1-R_s\bar{I}_{SR3}(2h)}. \quad (2.12)$$

Integrating expression (2.12), we find the reflection coefficient from a monocrystalline substrate with a structured surface, which is written as:

$$\bar{R}_m=\frac{1}{b}\int_0^b R_{\underline{BS}}(y)dy=R_{s2^*}+\frac{(1-R_{s2^*})(1-R_{s2})\bar{I}_{SR3}(2h)}{1-R_{s2}\bar{I}_{SR3}(2h)}. \quad (2.13)$$

Consider a layer of macroporous silicon. It has two scattering surfaces, so let's introduce the effective scattering angle. Thinking similarly to expressions (2.6) – (2.13), where the reflection coefficient from the monocrystalline substrate is determined, we write the reflection coefficient from the layer of macroporous silicon:

$$\bar{R}_{LP}=R_{s1^*}+\frac{(1-R_{s1^*})(1-R_{s1})R_{s2^*}\exp(\frac{-2\alpha h_1}{\cos(\theta_{eff})})}{1-R_{s1}R_{s2^*}\exp(\frac{-2\alpha h_1}{\cos(\theta_{eff})})}, \quad (2.14)$$

where θ_{eff} is the effective scattering angle of the frontal structured surface in the macroporous layer (see Fig. 1). The optical path travelled by light in a material increases if the effective scattering angle increases. Expression (2.14) contains the reflection coefficient from the second structured surface, when light propagates in the direction of macroporous silicon – silicon. Let us add to it the reflection coefficient from the monocrystalline substrate and obtain from expressions (2.13) and (2.14) an expression for finding the reflection coefficient from the structure of macroporous silicon:

$$\bar{R}_{\underline{PS}}=R_{s1^*}+\frac{(1-R_{s1^*})(1-R_{s1})\exp(\frac{-2\alpha h_1}{\cos(\theta_{eff})})}{1-R_{s1}R_{s2^*}\exp(\frac{-2\alpha h_1}{\cos(\theta_{eff})})}\times$$

$$\times\left(R_{s2^*}+\frac{(1-R_{s2^*})(1-R_{s2})\bar{I}_{SR3}(2h_2)}{1-R_{s2}\bar{I}_{SR3}(2h_2)}\right). \quad (2.15)$$

3. RESULTS AND DISCUSSION

Consider macroporous silicon. Light falls on macropores. We consider the macroporous silicon layer as an effective medium. The macroporous layer scatters light on the structured frontal surface both in the air-macroporous silicon (effective medium) direction and in the macroporous silicon-air direction. The second structured surface scatters light both in the macroporous silicon-silicon direction and in the silicon-macroporous silicon direction. The side surface of the macroporous silicon layer scatters light. The side surface of the monocrystalline substrate reflects according to the Fresnel law. The complex effective refractive index of the effective medium (macroporous silicon layer) is found from the expression:

$$n_{eff^*} = (1-P)n_{Si^*} + P\,, \tag{2.16}$$

where P is the volume fraction of pores, $n_{Si^*} = n_{Si} + ik_{Si}$ is the complex refractive index of silicon, and k is the extinction coefficient of silicon. The angle of total internal reflection from a flat rear surface when light propagates in the direction of silicon – air is calculated using the Snell's law. Part of the light reflected from the structured surface will be reflected at the angle of total internal reflection. The angle of total internal reflection exists for structured frontal and side surfaces, when light propagates in the direction of macroporous silicon - air, and for the second structured surface, when light propagates in the direction of silicon - macroporous silicon. We write the reflection coefficient from the structured frontal surface as:

$$R_{s1^*} = R_{s1} - R_{c1} = \mathrm{Re}\left|\frac{n_{eff^*}-1}{n_{eff^*}+1}\right|^2 =$$

$$= \left|\frac{(1-P)((n_{Si}-1)(1+P+n_{Si}(1-P)) + k_{Si}(1-P))}{(1+P+n_{Si}(1-P))^2 + (k_{Si}(1-P))^2}\right|^2, \tag{2.17}$$

where R_{c1} is the coefficient associated with total internal reflection from the structured frontal surface. The reflection coefficient from the second structured surface is written as:

$$R_{s2^*} = R_{s2} - R_{c2} = \mathrm{Re}\left|\frac{n_{eff^*}-n_{Si^*}}{n_{eff^*}+n_{Si^*}}\right|^2 =$$

$$= \left|\frac{P((n_{Si}-1)(P+n_{Si}(2-P)) + k_{Si}(2-P))}{(P+n_{Si}(2-P))^2 + (k_{Si}(2-P))^2}\right|^2, \tag{2.17}$$

where Rc_2 is the coefficient associated with total internal reflection from the second structured surface. We used the Snell's law for direct incidence because the reflection coefficient from a structured surface will be weakly dependent on the angle of incidence. It is also necessary to take into account the difference in reflectance associated with total internal reflection from a structured surface.

Fig. 2 shows the reflection spectrum from macroporous silicon 500 μm thick with a pore depth of 100 μm at different pore volume fractions. Curve one shows the reflection spectrum from a silicon single crystal. The reflection spectrum of silicon single crystal contains reflection from the frontal surface (air – a silicon single crystal), if the wavelength of light is from 0.3 μm to 1 μm (see Fig. 2, curve 1). This is observed due to the strong absorption of light with a wavelength less than 1 μm. Reflection from the frontal and rear surfaces of a silicon single crystal is observed for light lengths from 1 μm to 1.3 μm (see Fig. 2, curve 1). The reflection spectrum from macroporous silicon, with a pore depth of 100 μm and a pore volume fraction of 0.25, decreases with respect to the reflection spectrum from a silicon single crystal. (Fig. 2 curves 1 and 2). Two structured surfaces appeared when pores appeared. The frontal surface becomes structured and another structured surface appears, separating the macroporous layer and the monocrystalline substrate. These structured surfaces reflect, transmit and scatter light. We consider cases where a layer of macroporous silicon is an effective light-scattering medium. The effective medium has an effective refractive index that is less than the refractive index of silicon.

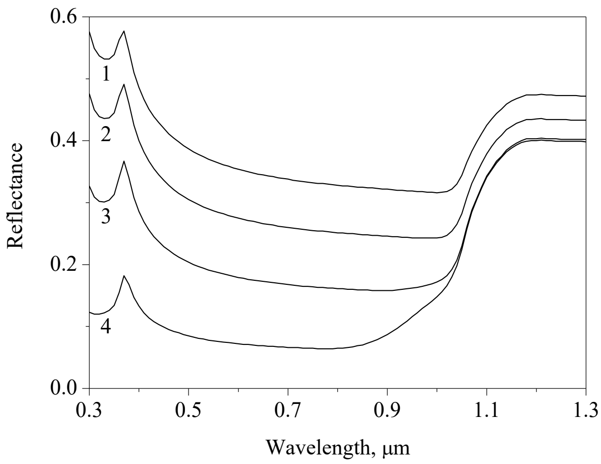

Fig. 2 – The reflection spectrum from macroporous silicon or arrays of silicon nanowires on a monocrystalline substrate with the volume fraction of pores: 1–0; 2–0.25; 3–0.5; 4–0.75. The pore depth is 100 μm

A decrease in the refractive index of a material leads to a decrease in reflection from its surface. With the appearance of pores, reflection from one flat surface in a single crystal was replaced by reflection from a layer of macroporous silicon, which is an effective medium with two structured surfaces. With an increase in the volume fraction of pores, the reflection from the structured frontal surface decreases, and from the second structured surface it increases (see Fig. 2). This is due to the fact that with an increase in the volume fraction of pores, the effective refractive index decreases. It varies from the effective refractive index of silicon to the refractive index of air. We observe reflection from the second structured surface when the volume fraction of pores is 0.75. That is, for light with wavelengths from 0.85 μm to 1 μm, the reflection from the structured front surface became less than the reflection from the second structured surface. Reflection from three surfaces is observed for light with wavelengths from 1 μm to 1.3 μm (see Fig. 2). Reflection from macroporous silicon (from three surfaces) is the same when the volume fraction of pores is 0.5 (Fig. 2, curve 3) and 0.75 (Fig. 2, curve 4). This is due to the increase in reflection from the second structured surface.

Fig. 3 shows the reflection spectrum from macroporous silicon 500 μm thick with a pore depth of 100 μm at a volume fraction of pores from 0.9 to 1. Curve one shows the reflection spectrum from a silicon single crystal. Curve 5 Fig. 3 shows that the reflection of light with wavelengths between 0.3 μm and 0.75 μm from macroporous silicon (reflection from the frontal structured surface) is 0.02, which is very low. The reflection of light with wavelengths between 0.75 μm and 1 μm from macroporous silicon (reflection from the frontal and second structured surfaces) increases with increasing wavelength and is significant. Fig. 3 shows that the reflection of light with wavelengths from 0.4 μm to 1 μm sharply increases with an increase in the volume fraction of pores from 0.9 to 1 (see curves 1 – 5).

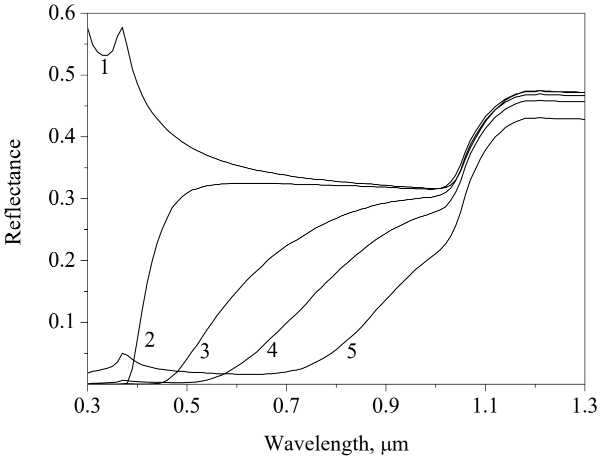

Fig. 3 – Reflection spectrum from macroporous silicon or arrays of silicon nanowires on a monocrystalline substrate with the volume fraction of pores: 1–0; 2–0.999; 3–0.99; 4–0.97; 5–0.9. The pore depth is 100 μm

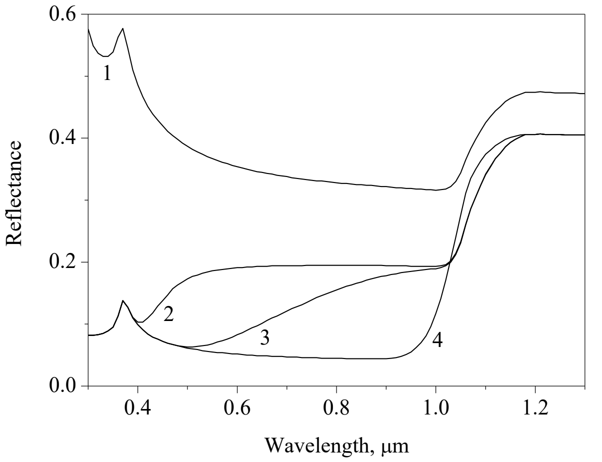

Fig. 4 – Reflection spectrum from macroporous silicon or arrays of silicon nanowires on a monocrystalline substrate with pore depth or nanowire length, μm: 1–0; 2–1; 3–10; 4–400. The volume fraction of pores is 0.8

An interesting fact is that the reflection of light with wavelengths from 0.4 μm to 1 μm decreases sharply at a wavelength of about 0.4 μm and is almost zero for wavelengths from 0.3 μm to 0.4 μm. It is difficult to provide such conditions, since it is necessary to have one nanowire with a diameter of 0.3 nm on an elementary area of 300 nm. A pore volume fraction of 0.99 can be realized. One nanowire with a diameter of 3 nm must be grown on an elementary area with a size of 300 nm. In addition, Fig. 3 shows that the reflection from macroporous silicon transforms into reflection from a single crystal at a pore volume fraction of 1.

Fig. 4 shows the reflection spectrum from macroporous silicon with different pore depths. The volume fraction of pores is 0.8. The first curve shows reflection spectrum from a silicon single crystal. The reflection spectrum of light with wavelengths from 1 μm to 1.3 μm from macroporous silicon does not change when the pore depth changes from 1 μm to 10 μm (see Fig. 4, curves 2 and 3). Curve 4 shows that the reflection spectrum from macroporous silicon with a pore depth of 400 μm has shifted relative to the reflection spectra from macro-porous silicon with a pore depth of 1 μm and 10 μm. This is due to the fact that the light reflected from the rear surface passes through the monocrystalline substrate, which has become thinner, and the more transparent macroporous layer, which has become thicker. The sample of macroporous silicon became more transparent. The reflection spectrum of light with wavelengths from 0.3 μm to 1 μm from macroporous silicon with a pore volume fraction of 0.8 depends on the pore depth (see Fig. 4). The light reflected from the second structured surface determines the reflection spectrum from the macroporous silicon sample in the range from 0.3 μm to 1 μm. It passes through the thickness of the macroporous layer, so the thicker the layer of macroporous silicon; the less light with short wavelengths will pass (see Fig. 4).

4. CONCLUSIONS

With an increase in the volume fraction of pores, the reflection from the frontal structured surface decreases, while the reflection from the second structured surface increases. Against the background of reflection from the frontal structured surface and the rear flat surface, reflection from the second structured surface is observed when the volume fraction of pores is 0.75.

The reflection of light with wavelengths from 0.4 μm to 1 μm sharply increases with an increase in the volume fraction of pores from 0.9 to 1. When the volume fraction of pores is greater than 0.95, the reflection of light from macroporous silicon decreases sharply at a wavelength of about 0.4 μm and is almost zero for wavelengths from 0.3 μm to 0.4 μm.

Macroporous silicon with a pore volume fraction greater than 0.95 can be a filter that will absorb wavelengths from 0.3 μm to 0.4 μm.

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Відбиття макропористого кремнію, нанодротин та двошарової структури кремнію з ефективним середовищем

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Представлена теоретична модель відбиття макропористого кремнію та масивів кремнієвих нанодротин на монокристалічній підкладці. Макропористий кремній та кремній структурований нанодротанами розглянутий як двошарова структура кремнію з ефективним середовищем. Аналітична модель відбиття від двошарової структури кремнію з ефективним середовищем враховує поглинання світла структурою та багаторазове відбиття світла від поверхонь зразка та поверхні між ефективним середовищем та монокристалічною підкладкою. Коефіцієнт відбиття від структурованої поверхні, яка є межею двох середовищ, містить комплексний показник заломлення кремнію. Ефективний показник заломлення ефективного середовища знаходиться з виразу для змішування двох середовищ. Відбиття світла падаючого на плоскі поверхні під різними кутами розраховується за формулами Френеля. Фронтальна структурована поверхня та друга структурована поверхня вважалися поверхнями Ламберта. Повне внутрішнє відбиття від плоскої поверхні між кремнієм та повітрям знаходиться за законом Снеліуса, а від структурованих поверхонь між кремнієм та ефективним середовищем та між ефективним середовищем та повітрям враховується за допомогою коефіцієнтів. Спектри відбиття від макропористого кремнію та масивів кремнієвих нанодротин на монокристалічній підкладці розраховані за аналітично виведеними формулами. Показано, що величина спектрів відбиття від макропористого кремнію зменшується коли об'ємна частка пор зростає. Відбиття знову починає збільшуватись тоді, коли об'ємна частка пор є високою. Відбиття від поверхні між ефективним середовищем та повітрям проявляється при високій об'ємній частці пор.

Ключові слова: Макропористий кремній, Чорний кремній, Нонодротини, Коефіцієнт відбиття, Спектр відбиття.