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REGULAR ARTICLE

Reflection and Absorption of Two-Layer Porous Silicon

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The reflection and absorption of two-layer porous silicon was calculated. Two-layer porous silicon has less reflection than single-layer porous silicon and single-crystal silicon. The reflectance of two-layer porous silicon decreases to a certain value, and then it increases when the volume fraction of the pores of the first layer of porous silicon increases. The volume fraction of the pores of the first layer of porous silicon is greater than the volume fraction of the pores of the second layer of porous silicon. Layers of porous silicon are considered effective media. The lowest reflection of two-layer macroporous silicon is found by optimizing the volume fraction of pores of each layer of porous silicon. The decrease in reflection of two-layer porous silicon compared to the reflection of porous silicon with one layer of macropores is explained. The reflection of two-layer porous silicon exceeds the reflection of single-layer porous silicon and single-crystal silicon when the volume fraction of the pores of the first layer of porous silicon is small and that of the second layer of porous silicon is large. The absorption of two-layer porous silicon with optimized pore volume fractions is 0.88.

Keywords: Reflection, Transmission, Two-layer porous silicon.

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1. INTRODUCTION

Porous silicon, nanowires, pyramids and cones on the surface reduce light reflection. Reducing the reflection of light increases the absorption of the solar cell. 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 [1]. The front and rear structured surfaces of the solar cell affect light trapping and its quantum efficiency. The frontal structured surface improves the light absorption and quantum efficiency of the solar cell in a wide range of light wavelengths. The back structured surface increases the quantum efficiency of the solar cell for wavelengths of light greater than 0.6 μm. A solar cell with a structured surface shows the best ratio between front surface absorption, light scattering efficiency and losses [2]. The reflection of two-layer structures with a layer of nanowires and macropores is calculated using a numerical method. Scattering of light on the surfaces of porous layers is taken into account. The reflection of two-layer structures depends on the volume fraction of pores [3]. Graded photonic supercrystals exhibit broadband light absorption. Light is captured at different angles of incidence and regardless of its polarization. Increased light absorption is associated with the dispersion of the refractive index of light in space [4]. Light capture improves with increasing depth of the photonic structure on the surface of the solar cell. The angular distribution of light intensity in photonic structures is smaller compared to a Lambertian scatterer, but absorption is improved due to direction-dependent light transmission [5]. Oscillations in the absorption spectra of macroporous silicon structures with surface nanocrystals are analyzed. Oscillations are observed in the infrared region of the spectrum [6]. The kinetics of porous silicon charge carriers is calculated using a numerical method. Porous silicon has two porous layers that are placed on different sides of a monocrystalline substrate. The pore depth affects the effective lifetime of charge carriers [7]. Two-layer macroporous silicon is being studied. The effective lifetime of charge carriers is found. Equations for calculating the effective lifetime of charge carriers are derived. The dependence of the effective lifetime of charge carriers on the depth of the macropores of each porous layer is analyzed [8]. The velocity of volume and surface recombination of single-crystal silicon nanowires was determined by an optical method. The speed of surface recombination on the passivated surface of nanowires, determined using the dynamics of spatially limited electron-hole matter, is equal to 0.2 m/s. This rate of surface recombination indicates very high-quality surface passivation of single-crystal silicon nanowires. The bulk recombination rate of single-crystal silicon nanowires is no different from that of high-quality single-crystal silicon. Nanowires were grown by the vapor-liquid-solid method, where gold was used as a catalyst [9]. The correlation between current transport, oxidation quality of porous silicon and dielectric relaxation show the presence of

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two main current transport pathways. In oxidized porous silicon, another mechanism of interphase polarization relaxation is observed. It is observed at high temperatures and has a long relaxation time [10]. Measured thermoelectric properties of layers of nanostructured porous silicon grown on monocrystalline silicon substrates. For layers with different volume fraction of pores and size of nanocrystals: electrical conductivity and thermal conductivity were measured. A strong dependence of these values on the characteristics of nanoporous silicon layers was revealed [11].

2. REFLECTION AND TRANSMISSION OF TWO-LAYER POROUS SILICON

Let there be two-layer porous silicon. Two layers of porous silicon with different volume fraction of pores are located on a monocrystalline substrate. The reflection of the porous silicon plate is expressed by the sum [3]:

$$R_1 = R_{s1} + (1-R_{s1})^2 \sum_{n=1}^{\infty} (R_{s1}^{n-1} R_{s2}^{n} \exp(-2\alpha_1 n h_1)) \, , \quad (2.1)$$

where R_{s1} is the reflection of the boundary between air and the first layer of porous silicon, R_{s2} is the reflection of the boundary between the first and second layers of porous silicon, α_1 is the effective refractive index of the first layer of porous silicon, n is the reflection number, h_1 is the pore depth of the first layer of porous silicon. The sum in expression (2.1) is equal to a fraction, so expression is written as follows:

$$R_1 = R_{s1} + \frac{(1-R_{s1})^2 R_{s2} \exp(-2\alpha_1 h_1)}{1 - R_{s1} R_{s2} \exp(-2\alpha_1 h_1)} \, . \quad (2.2)$$

Light passes through the first layer of porous silicon, reflects off the second layer of porous silicon, and passes through the first layer of porous silicon. The reflection from two layers of porous silicon is written as follows:

$$\begin{aligned} R_2 &= R_{s1} + (1-R_{s1})^2 \sum_{n=1}^{\infty} (R_{s1}^{n-1} R_{s2}^{n-1} \exp(-2\alpha_1 n h_1)) \times \\ &\times (R_{s2} + (1-R_{s2})^2 \sum_{m=1}^{\infty} (R_{s2}^{m-1} R_{s3}^{m} \exp(-2\alpha_2 m h_2))) \end{aligned} \, , \quad (2.3)$$

where R_{s3} – reflection of the boundary between the second layers of porous silicon and the monocrystalline substrate, α_2 is the effective index of refraction of the second layer of porous silicon, m is the reflection number, h_2 is the pore depth of the second layer of porous silicon. The sums in expression (2.3) are equal to fractions, so expression (2.3) is written as follows:

$$\begin{aligned} R_2 &= R_{s1} + \frac{(1-R_{s1})^2 \exp(-2\alpha_1 h_1)}{1 - R_{s1} R_{s2} \exp(-2\alpha_1 h_1)} \times \\ &\times (R_{s2} + \frac{(1-R_{s2})^2 \exp(-2\alpha_2 h_2) R_{s3}}{1 - R_{s2} R_{s3} \exp(-2\alpha_2 h_2)}) \end{aligned} \, , \quad (2.4)$$

Light rays pass through the first and second layers of porous silicon and the monocrystalline substrate, reflecting many times in the middle of each layer. The resulting reflection is written as:

$$\begin{aligned} R_{31} &= (1-R_{s1})^2 \left(\sum_{n=1}^{\infty} (R_{s1}^{n-1} R_{s2}^{n-1} \exp(-2\alpha_1 n h_1)) \right)^2 \times \\ &\times \left((1-R_{s2})^2 \sum_{m=1}^{\infty} (R_{s2}^{m-1} R_{s3}^{m-1} \exp(-2\alpha_2 m h_2)) \right)^2 \times \\ &\times (1-R_{s3})^2 \sum_{k=1}^{\infty} (R_{s3}^{k-1} R_{s4}^{k} \exp(-2\alpha k h_3)) \end{aligned} \, , \quad (2.5)$$

where R_{s4} is the reflection of the boundary between the monocrystalline substrate and air, α is the refractive index of monocrystalline silicon, k is the reflection number, h_3 is the thickness of the monocrystalline substrate. Light passes through two layers of porous silicon and a monocrystalline substrate, is reflected from the boundary of the monocrystalline substrate with air, and again passes through the monocrystalline substrate and two layers of porous silicon, is reflected again, and so on. The resulting reflection is written as:

$$\begin{aligned} R_{32} &= R_{31} \sum_{n=1}^{\infty} \left(\left(\sum_{k=1}^{\infty} (R_{s2}^{k-1} R_{s1}^{k} \exp(-2\alpha_1 k h_1)) \right)^{n-1} \times \right. \\ &\times \left((1-R_{s3})^2 \sum_{l=1}^{\infty} (R_{s2}^{l-1} R_{s3}^{l} \exp(-2\alpha_2 l h_2)) \right)^{n-1} \times \\ &\left. \times \left((1-R_{s2})^2 \sum_{m=1}^{\infty} (R_{s3}^{m-1} R_{s4}^{m} \exp(-2\alpha m h_3)) \right)^{n-1} \right) \end{aligned} \, , \quad (2.6)$$

where l is the reflection number. The sums in expressions (2.5) and (2.6) are equal to fractions, so expression (2.6) is written as follows:

$$\begin{aligned} R_{32} &= \frac{(1-R_{s1})^2 (1-R_{s2})^2 \exp(-2\alpha_1 h_1)}{(1 - R_{s1} R_{s2} \exp(-2\alpha_1 h_1))^2} \times \\ &\times \frac{(1-R_{s3})^2 R_4 \exp(-2\alpha h_3) R_{s4}}{(1 - R_{s3} R_{s4} \exp(-2\alpha h_3)} \times \\ &\times \frac{\exp(-2\alpha_2 h_2)}{(1 - R_{s2} R_{s3} \exp(-2\alpha_2 h_2)^2 R_{33}} \end{aligned} \, , \quad (2.7)$$

where:

$$\begin{aligned} R_{33} &= 1 - \frac{(1-R_{s2})^2 \exp(-2\alpha_1 h_1) R_{s1}}{(1 - R_{s1} R_{s2} \exp(-2\alpha_1 h_1))} \times \\ &\times \frac{(1-R_{s3})^2 \exp(-2\alpha h_3) R_{s4}}{(1 - R_{s3} R_{s4} \exp(-2\alpha h_3))} \times \\ &\times \frac{\exp(-2\alpha_2 h_2)}{(1 - R_{s2} R_{s3} \exp(-2\alpha_2 h_2)^2} \end{aligned} \, . \quad (2.8)$$

Taking into account the reflection of the first and second layers of porous silicon ((2.2) and (2.4)) and the reflection from expression (2.7), the reflection of two-layer porous silicon (on a monocrystalline substrate) is written as:

$$\begin{aligned} R_3 &= R_1 + \frac{(1-R_{s1})^2 \exp(-2\alpha_1 h_1)}{1 - R_{s1} R_{s2} \exp(-2\alpha_1 h_1)} \times \\ &\times \frac{(1-R_{s2})^2 \exp(-2\alpha_2 h_2)}{1 - R_{s2} R_{s3} \exp(-2\alpha_2 h_2)} R_{s3} + R_{32} \end{aligned} \, . \quad (2.9)$$

The transmission of light that passed through two layers of porous silicon and a monocrystalline substrate is written as:

$$T_1 = (1 - R_{s1})\exp(-2\alpha_1 h_1)(1 - R_{s2}) \times \\ \times \exp(-2\alpha_2 h_2)(1 - R_{s3})\exp(-2\alpha h_3)(1 - R_{s4}) \,. \quad (2.10)$$

Part of the light will be reflected in each layer many times, so its reflections will be written as a product of sums as follows:

$$T_2 = \frac{(1 - R_{s1})(1 - R_{s2})\exp(-2\alpha_1 h_1)}{(1 - R_{s1}R_{s2}\exp(-2\alpha_1 h_1))} \times \\ \times \frac{(1 - R_{s3})(1 - R_{s4})\exp(-2\alpha h_3)}{(1 - R_{s3}R_{s4}\exp(-2\alpha h_3)} \times \quad , \qquad (2.11) \\ \times \frac{\exp(-2\alpha_2 h_2)}{(1 - R_{s2}R_{s3}\exp(-2\alpha_2 h_2)}$$

Light passes through two layers of porous silicon and a monocrystalline substrate, is reflected from the interface of the monocrystalline substrate with air, and again passes through the monocrystalline substrate and two layers of porous silicon, is reflected again, and so on. Light transmission is recorded as:

$$T_3 = T_2 \sum_{n=1}^{\infty}\left(\left(\sum_{k=1}^{\infty}(R_{s2}^{k-1}R_{s1}^{k}\exp(-2\alpha_1 k h_1))\right)^{n-1} \times \right. \\ \times \left(\sum_{m=1}^{\infty}(R_{s3}^{m-1}R_{s4}^{m}\exp(-2\alpha m h_3))\right)^{n-1} \times \qquad .(2.12) \\ \left. \times \left(\sum_{m=1}^{\infty}(R_{s2}^{m-1}R_{s3}^{m}\exp(-2\alpha_2 m h_2))\right)^{n-1}\right)$$

The sums in expressions (2.11) and (2.12) are equal to fractions. From expressions (2.11) and (2.12), the transmission of two-layer porous silicon (on a monocrystalline substrate) is written as follows:

$$T_3 = \frac{(1 - R_{s1})(1 - R_{s2})(1 - R_{s3})(1 - R_{s4})}{(1 - R_{s1}R_{s2}\exp(-2\alpha_1 h_1))(1 - R_{s3}R_{s4}\exp(-2\alpha h_3)} \times \\ \times \frac{\exp(-2(\alpha_1 h_1 + \alpha_2 h_2 + \alpha h_3))}{(1 - R_{s2}R_{s3}\exp(-2\alpha_2 h_2)^2 R_{33}} \, .(2.13)$$

3. RESULTS AND DISCUSSION

Fig. 1 shows a diagram of two-layer porous silicon with different volume fraction of pores for the first and second layers of porous silicon. The volume fraction of the pores of the first layer is smaller than the volume fraction of the pores of the second layer of porous silicon (see Fig. 1a). The volume fraction of the pores of the first layer is greater than the volume fraction of the pores of the second layer of porous silicon (see Fig. 1b). The first and second layers of porous silicon have pore depths h_1, h_2, respectively. The thickness of two-layer porous silicon (on a monocrystalline substrate) is equal to h. Light falls on the first layer of porous silicon and penetrates through the pores and monocrystalline silicon between the pores into the second layer of porous silicon and the monocrystalline substrate. Light is reflected many times at the boundaries of the porous silicon layers and the monocrystalline substrate. These boundaries partially transmit light at each reflection. Arrows near each porous layer and monocrystalline substrate show multiple reflection and transmission of light at the boundaries of the porous silicon layer and monocrystalline substrate.

Fig. 2 shows the dependence of the reflection of two-layer porous silicon on the volume fraction of pores in each porous layer. The wavelength incident on two-layer porous silicon is 0.95 μm. The volume fraction of the pores of each porous layer changes with an interval of 0.1. Fig. 2 shows that the dependence of the reflection of two-layer porous silicon on the volume fraction of the pores of the first layer of porous silicon has a minimum when the volume fraction of the pores of the second layer of porous silicon is less than 1. The reflection of two-layer porous silicon depending on the volume fraction of the pores of the second layer of porous silicon has a minimum when the volume fraction of pores of the first layer of porous silicon is greater than 0.6. In the P_1P_2 plane, the projection of the dependence of the reflectance of two-layer porous silicon on the volume fraction of the pores of each porous layer is shown. The projection of the reflectance dependence is shown by curves with the same reflectance of two-layer porous silicon for different volume fractions of the pores of the

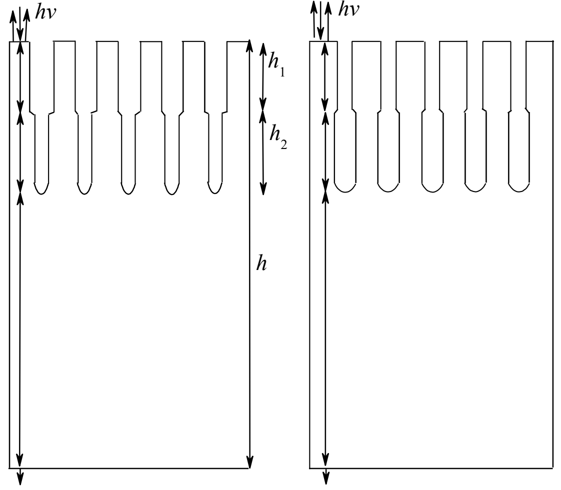

Fig. 1 – Schemes of two-layer porous silicon with different volume fractions of the pores of the first and second layers of porous silicon

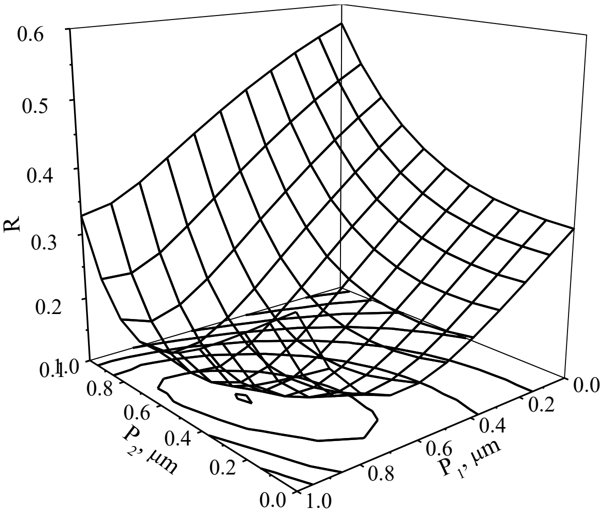

Fig. 2 – Dependence of the reflectance of two-layer porous silicon on the volume fraction of pores in each porous layer. The wavelength of light incident on two-layer porous silicon is 0.95 μm

first and second layers of porous silicon. The curves of the same reflection converge in a small circle, where the minimum reflection is located. The minimum dependence of the reflection of two-layer porous silicon on the volume fraction of the pores of each porous layer is observed when the volume fractions of the pores of the first and second layers of porous silicon are equal to 0.8, 0.5, respectively (see Fig. 2, projection).

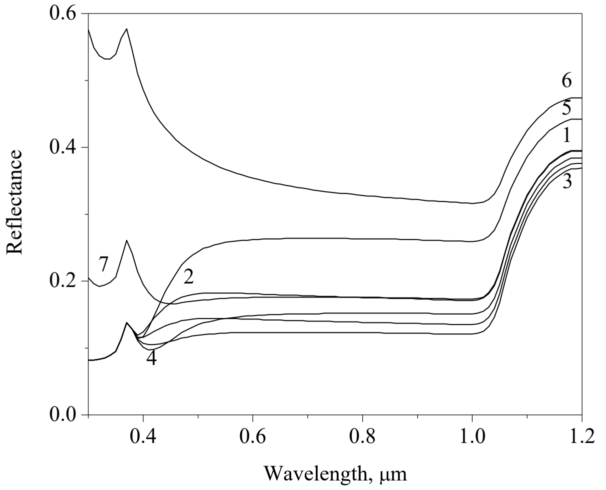

Fig. 3 – Spectral dependence of the reflection of two-layer porous silicon, when the volume fraction of the pores of the second layer of porous silicon: 1 – 0.1; 2 – 0.3; 3 – 0.5; 4 – 0.7; 5 – 0.9; 6 – 0 ($P_2 = 0$). The volume fraction of the pores of the first layer of porous silicon is 0.8. Curve 7 shows the reflection dependence of single-layer porous silicon with a volume fraction of pores of 0.655

Fig. 3 shows the spectral dependence of the reflectance of two-layer porous silicon at different volume fractions of the pores of the second layer of porous silicon. The volume fraction of the pores of the first layer of porous silicon is 0.8. The reflectance spectra of single-crystal silicon (curve 6) and single-layer porous silicon with an optimal pore volume fraction (curve 7) are shown for comparison with the absorption of two-layer porous silicon. Curve 1 from Fig. 3 shows the reflection dependence of single-layer porous silicon with a volume fraction of pores of 0.8. The reflection dependence of the two-layer porous silicon decreases by 0.05 when a second layer of porous silicon with a pore volume fraction of 0.1 appears. An increase in the volume fraction of the pores of the second layer of porous silicon to 0.3 and 0.5 leads to a decrease in the reflection of the two-layer porous silicon (see curves 2, 3). Dependence of the reflection spectrum of single-layer porous silicon with an optimal volume fraction of pores of 0.655 (curve 7) and the reflection spectrum of two-layer porous silicon with volume fractions of pores of the first and second layers of porous silicon of 0.8 and 0.1, respectively (curve 1) almost coincide for light with wavelengths from 0.45 μm to 1.2 μm. The smallest reflection spectrum of two-layer porous silicon is observed when the volume fractions of the pores of the first and second layers of porous silicon are 0.8 and 0.5, respectively (see Fig. 3, curve 3). The difference between the smallest reflectance spectra of two-layer porous silicon and single-layer porous silicon is 0.07 for light with wavelengths from 0.45 μm to 1.1 μm. Curve 4 from Fig. 2 shows that the reflectance of two-layer porous silicon can increase when the volume fraction of the pores of the second layer of porous silicon is less than the volume fraction of the pores of the first layer of porous silicon. The reflectance of the two-layer porous silicon initially decreases when the volume fraction of the pores of the second layer of porous silicon increases from zero to 0.5, and then the reflectance increases again. The transmittance of bilayer porous silicon has the opposite location of the curves for light with wavelengths between 1.1 μm and 1.2 μm due to the fact that light with these wavelengths is weakly absorbed.

Fig. 4 shows the spectral dependence of the absorption of two-layer porous silicon at different volume fractions of the pores of the second layer of porous silicon. The volume fraction of the pores of the first layer of porous silicon is 0.8. The absorption spectra of single-crystal silicon (curve 6) and single-layer porous silicon with an optimized pore volume fraction of 0.655 (curve 7) are shown for comparison with the absorption of two-layer porous silicon. Two-layer porous silicon absorbs light better than single-crystal silicon in the range of light wavelengths from 0.3 μm to 1.2 μm.

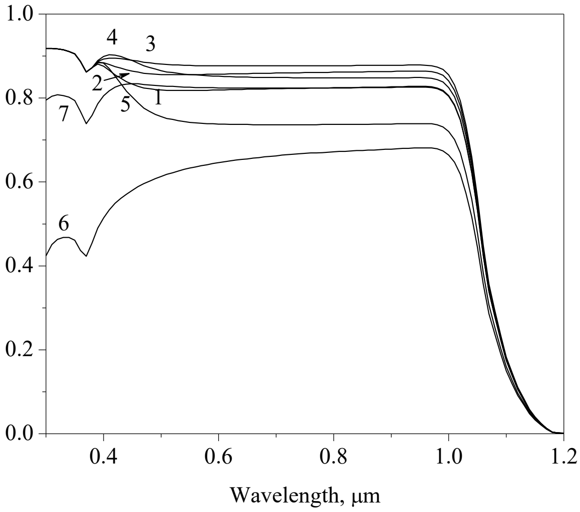

Fig. 4 – Spectral dependence of the absorption of two-layer porous silicon, when the volume fraction of the pores of the second layer of porous silicon is: 1 – 0.1; 2 – 0.3; 3 – 0.5; 4 – 0.7; 5 – 0.9; 6 – 0 ($P_2 = 0$). The volume fraction of the pores of the first layer of porous silicon is 0.8. Curve 7 shows the absorption dependence of single-layer porous silicon with a volume fraction of pores of 0.655

The reflection of two-layer porous silicon light with wavelengths from 0.3 μm to 1 μm determines its absorption, due to the complete absorption of light with these wavelengths. Two-layer porous silicon with different volume fractions of the pores of the second layer of porous silicon has the same light reflection with wavelengths from 0.3 to 0.4 (see Fig. 4 curves 1-5). The spectral dependence of absorption of two-layer porous silicon with a volume fraction of pores of the second layer of porous silicon from 0.1 to 0.7 exceeds the spectral dependence of absorption of single-layer porous silicon with an optimized volume fraction of pores of 0.655. The absorption of two-layer porous silicon with a volume fraction of pores of the second layer of porous silicon of 0.9 is significantly reduced due to the increase in reflection from the interface between the second layer of porous silicon and the monocrystalline substrate. The reflection from this limit increased due to the high contrast between the effective refractive index of the second layer of porous silicon and the refractive index of the monocrystalline substrate.

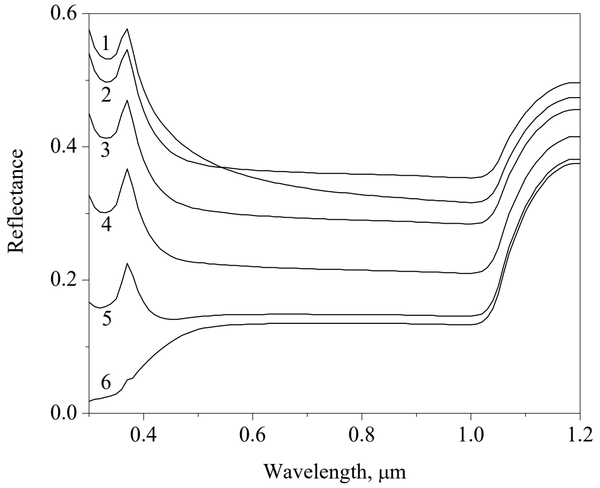

Fig. 5 – Spectral dependence of the reflection of two-layer porous silicon, when the volume fraction of the pores of the first layer of porous silicon: 1 – 0 (P_2 = 0); 2 – 0.1; 3 – 0.3; 4 – 0.5; 5 – 0.7; 6 – 0.9. The volume fraction of the pores of the second layer of porous silicon is 0.6

Fig. 5 shows the spectral dependence of the reflection of two-layer porous silicon with different volume fraction of pores of the first layer of porous silicon. The volume fraction of the pores of the second layer of porous silicon is 0.6. Curve 1 from Fig. 5 shows the spectral dependence of the reflectance of single-crystal silicon for comparison with the reflectance of two-layer porous silicon. The dependence of the reflectance of two-layer porous silicon with a volume fraction of the pores of the first layer of porous silicon of 0.1 is greater than the reflectance of single-crystal silicon for light with wavelengths from 0.55 μm to 1.2 μm. Two-layer porous silicon has a higher reflectance than monocrystalline silicon, due to the high difference between the refractive index of air and the effective refractive index of the first layer of porous silicon at the interface between air and the first layer of porous silicon. Reflectance from the boundaries of the second layer of porous silicon with the first layer of porous silicon and the monocrystalline substrate further increase the reflection of the two-layer porous silicon. The spectral dependence of the reflectance of two-layer porous silicon decreases uniformly when the volume fraction of the pores of the first layer of porous silicon decreases to 0.7 for wavelengths of light from 0.3 μm to 1.2 μm (see Fig. 5, curves 2-5). The reflectance of two-layer porous silicon with pore volume fractions of 0.8 and 0.9 has not much difference because the first layer of porous silicon disappears and only the second layer of porous silicon remains

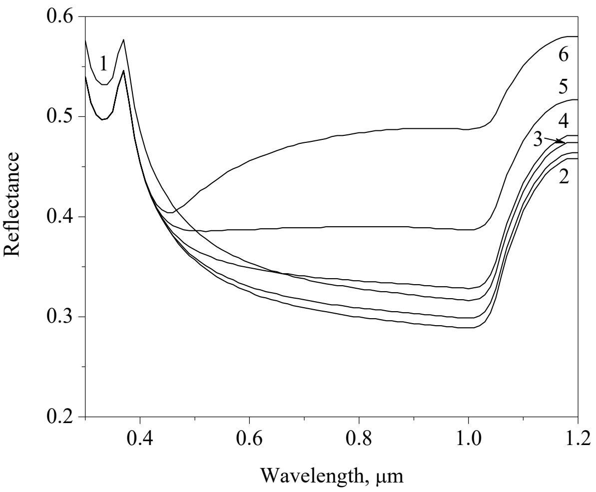

Fig. 6 – Spectral dependence of the reflection of two-layer porous silicon, when the volume fraction of the pores of the second layer of porous silicon: 1 – 0 (P_2 = 0); 2 – 0.1; 3 – 0.3; 4 – 0.5; 5 – 0.7; 6 – 0.9. The volume fraction of the pores of the first layer of porous silicon is 0.1

Fig. 6 shows the spectral dependence of the reflectance of two-layer porous silicon at different volume fractions of the pores of the second layer of porous silicon. The volume fraction of the pores of the first layer of porous silicon is 0.1. Curve 1 from Fig. 5 shows that the spectral dependence of the reflection of two-layer porous silicon with volume fractions of the pores of the porous silicon layers of 0.6 and 0.1, respectively, exceeds the reflection of single-crystal silicon, so the volume fraction of the pores of the first layer of porous silicon should be reduced. Curve 1 from Fig. 6 shows the spectral dependence of the reflectance of single-crystal silicon. Spectral dependences of reflectance of two-layer porous silicon with volume fractions of pores of the second layer of porous silicon of 0.1 and 0.3 are less than the spectral dependence of reflection of single-crystal silicon for light with wavelengths from 0.48 μm to 1.2 μm. The reflection spectrum of two-layer porous silicon with a volume fraction of the pores of the first layer of porous silicon of 0.1 does not depend on the volume fraction of pores of the second layer of porous silicon in the range of wavelengths of light from 0.3 μm to 0.48 μm. This reflection spectrum is smaller than the reflection spectrum of a silicon single crystal. A sharp increase in the reflection spectra is observed for two-layer porous silicon with volume fractions of pores of the second layer of porous silicon from 0.5 to 0.9 (see Fig. 6, curves 4-6). The reflectance of two-layer porous silicon with a volume fraction of the pores of the second layer of porous silicon of 0.9 exceeds the reflectance of single-crystal silicon by an average of 0.15 for light with a wavelength of 1 μm and by 0.1 for the interval of light lengths from 1 μm to 1.2 μm (see Fig. 6, curve 6).

4. CONCLUSIONS

The smallest reflection spectrum of two-layer porous silicon is observed when the volume fractions of the pores of the first and second layers of porous silicon are 0.8 and 0.5, respectively. The difference between the smallest reflectance spectra of two-layer porous silicon and single-layer porous silicon is 0.07 for light with wavelengths from 0.45 μm to 1.1 μm. The reflectance of two-layer porous silicon first decreases when the volume fraction of the pores of the second layer of porous silicon increases from zero to 0.5 (the volume fraction of the pores of the first layer of porous silicon is 0.8), and then the reflectance increases again.

The spectral dependence of the absorption of two-layer porous silicon with a volume fraction of the pores of the second layer of porous silicon from 0.1 to 0.7 (the volume fraction of the pores of the first layer of porous silicon is 0.8) exceed the spectral dependence of the absorption of single-layer porous silicon with an optimized volume with a proportion of pores of 0.655. The absorption of two-layer porous silicon with a volume fraction of pores of the second layer of porous silicon of 0.9 is significantly reduced due to the increase in reflection from the interface between the second layer of porous silicon and the monocrystalline substrate. The reflection from this interface increased due to the high contrast between the effective refractive index of the second layer of porous silicon and the refractive index of the monocrystalline substrate.

REFERENCES

1. L. Tsakalakos, J. Balch, J. Fronheiser, B.A. Korevaar, O. Sulima, J. Rand, *Appl. Phys. Lett.* **91**, No 23, 233117 (2007).
2. H. Sai, H. Jia, M. Kondo, *J. Appl. Phys.* **108** No 4, 044505 (2010).
3. V.F. Onyshchenko, *J. Nano- Electron. Phys.* **15** No 3, 03026 (2023).
4. S. Hassan, D. Lowell, M. Adewole, D. George, H. Zhang, Y. Lin, *Photonics* **4** No 4, 50 (2017).
5. T. Tayagaki, Y. Kishimoto, Y Hoshi, N. Usami, *Appl. Phys. Express* **7**, 122301 (2014).
6. L.A. Karachevtseva, O.O. Lytvynenko, *Semiconductor Physics, Quantum Electronics & Optoelectronics* **20** No 3, 316 (2020).
7. V.F. Onyshchenko L.A. Karachevtseva, K.V. Andrieieva, N.V. Dmytruk, A.Z. Evmenova, *Semiconductor Physics, Quantum Electronics & Optoelectronics* **26** No 2, 159 (2023).
8. V.F. Onyshchenko, *J. Nano- Electron. Phys.* **16** No 4, 04026 (2024).
9. O. Demichel, V. Calvo, A. Besson, P. Noe, B. Salem, N. Pauc, F. Oehler, P. Gentile, N. Magnea *Nano Lett.* **10** No 7, 2323 (2010).
10. B. Urbach, E. Axelrod, A. Sa'ar, *Phys. Rev. B* **75** No 20, 205330 (2007).
11. R.J. Martín-Palma, H. Cabrera, B. Martín-Adrados, D. Korte, E. Perez-Cappe, Y. Mosqueda, M.A. Frutis, E. Danguillecourt, *Mater. Res. Express* **5**, 015004 (2018).

Відбиття та поглинання двошарового пористого кремнію

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Розраховано відбиття та поглинання двошарового пористого кремнію. Двошаровий пористий кремній має відбиття менше за одношаровий пористий кремній та монокристал кремнію. Відбиття двошарового пористого кремнію зменшується до певної величини, але потім зростає, коли об'ємна частка пор першого шару пористого кремнію зростає. Об'ємна частка пор першого шару пористого кремнію більша за об'ємну частку пор другого шару пористого кремнію. Шари пористого кремнію розглядаються як ефективні середовища. Найменше відбиття двошарового макропористого кремнію знаходиться оптимізацією об'ємних часток пор кожного шару пористого кремнію. Пояснюється зменшення відбиття двошарового пористого кремнію в порівнянні з відбиттям пористого кремнію з одним шаром макропор. Відбиття двошарового пористого кремнію перевищує відбиття одношарового пористий кремній та монокристалу кремнію, коли об'ємна частка пор першого шару пористого кремнію мала, а другого шару пористого кремнію велика. Поглинання двошарового пористого кремнію з оптимізованими об'ємними частками пор дорівнює 0,88.

Ключові слова: Відбиття, Пропускання, Двошаровий пористий кремній.