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METHOD OF MEASURING NON-EQUILIBRIUM CARRIERS CONCENTRATION AND THEIR LIFETIME IN A SEMICONDUCTOR USING THE APPROACH OF A PHOTONIC CRYSTAL WITH A DEFECT MODE

The purpose of this paper is an experimental investigation of the influence of properties of the silicon defect layer in a dielectric photonic crystal on the transmission peak spectral properties. The influence of the defect layer thickness on the defect mode frequency is shown. The possibility of changing characteristics of transmission peak by green laser illumination of the silicon layer is demonstrated and analyzed using a photonic crystal approach. It is experimentally found that illumination leads to a decrease of transmission coefficient value at the defect mode frequency, but does not lead to a change of this peak frequency. The non-equilibrium carriers concentration and their lifetime have been evaluated. The results of this paper can be used in manufacturing controllable circuits in millimeter waveband and the approach can be used in semiconductors manufacture as non-destructive control of semiconductors properties method. Fig. 6. Bibl.: 17 titles.

Key words: semiconductor, photonic crystal, defect layer, non-equilibrium carriers.

Photonic crystals (PCs) are the structures with a spatially periodically changing refractive index [1]. The main property of PCs is the existence of allowed bands and bandgaps in frequency transmission spectra of electromagnetic waves. This property allows using PCs as a frequency filters, low-loss waveguides, optical computers, and beam switches [2]. For using photonic crystals as the main components of electronic and optical devices, it is necessary for them to be tunable. It allows improving their efficiency and expanding the range of application. It is possible to create PCs in millimeter waveband tunable by external permanent magnetic field. For this reason the structures from dielectrics and ferrites are used [3]. The presence of semiconductor layers in PCs should make it possible to control spectral properties by using the external effects like temperature [4], illumination [5], and injection of inhomogeneities in a semiconductor layer [6]. It is necessary to use semiconductors to create light controllable PCs [7], because there is photoconductivity in the semiconductors. It is important that existence of only one semiconductor layer is enough for effective control of the whole structure properties. As it is known, irregularity of periodicity may lead to an occurrence of the transmission peak in the bandgap. This effect may be coupled with a defect mode occurrence [8, 9] or, in special case, surface electromagnetic (Tamm) state occurrence [7]. Thereat, the illumination of the semiconductor layer may lead to a change of the peak intensity, width and frequency. For the surface oscillation peak it is necessary, that permittivity of the semiconductor should be negative in the required frequency range. These values of permittivity are achieved at high doping levels. However, it is impossible to use semiconductors with high doping levels in the millimeter wavelength range because of high losses in them [10]. For the defect mode formation it is preferable to use the high-ohmic semiconductors as defect layers. The optical range illumination of them may lead to huge changes in spectral properties of PCs. Silicon is one of the most common semiconductors. The high-ohmic silicon has low losses in the millimeter waveband and herewith high sensitivity to illumination that makes it possible to use the high-ohmic silicon as a photosensitive layer in PCs. However, using layers with different thickness and equilibrium carriers concentration gives the possibility to obtain different values of non-equilibrium concentration caused by illumination.

Therefore, the purpose of this paper is an experimental investigation of illumination influence on the transmission spectrum of the photonic crystal quartz/polystyrene with a silicon defect layer, study of the silicon layer thickness influence on the transmission peak frequency, as well as numerical evaluation of concentration and lifetime of non-equilibrium carriers in silicon with different equilibrium concentration.

1. Photonic crystal with a defect silicon layer. In this paper we investigate 1D PC [3, 4] from quartz and polystyrene layers. As a defect layer, we use silicon with a hole type of conductivity. Its resistivity is of 20 kOhm·cm. The structure consists of 7 periods quartz/polystyrene, then period quartz/silicon is located, and then another 7 periods quartz/polystyrene. The graphic pattern is presented in Fig. 1. Permittivity of quartz equals $\varepsilon_1' = 3.8$, thickness $d_1 = 1.5$ mm; permittivity of polystyrene is $\varepsilon_2' = 2.5$ (we neglect the ε'' value for quartz and polystyrene), thickness $d_2 = 1$ mm. It is known, that permittivity of silicon is quite well described with Drude model [10, 11]:

$$\varepsilon_{\text{Si}} = \varepsilon_p \left[1 - \frac{\omega_{pn}^2}{\omega(\omega + i\nu_n)} - \frac{\omega_{pp}^2}{\omega(\omega + i\nu_p)} \right], \quad (1)$$

where ω_{pn}, ω_{pp} are plasma frequencies of electrons and holes in the semiconductor, ν_n, ν_p are electrons and holes collision frequencies, $\varepsilon_p = 11.8$ is the lattice part of silicon permittivity, ω is the circular frequency of an incident electromagnetic wave.

Expression for electrons and holes plasma frequencies is:

$$\omega_{pn,p} = \sqrt{4\pi e^2 n, p \big/ m_{n,p}^* \varepsilon_p}, \quad (2)$$

where n, p are electrons and holes concentration, respectively; $m_{n,p}^*$ are effective masses of charge carriers; $e = 1.6 \cdot 10^{-19}$ C is the electron charge.

Collision frequencies are coupled with carriers mobility and are determined as:

$$\nu_{n,p} = e \big/ \mu_{n,p} m_{n,p}^*, \quad (3)$$

where $\mu_{n,p}$ are electrons and holes mobility.

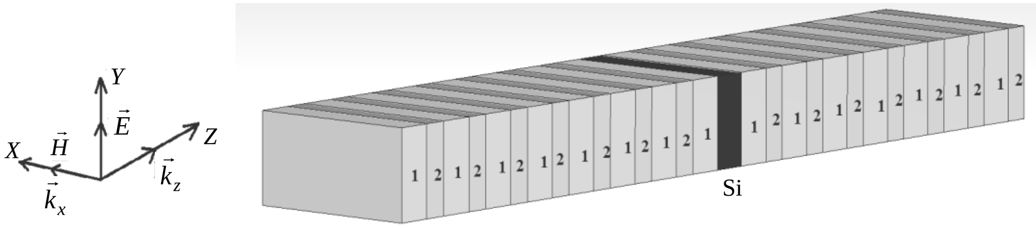

Fig. 1. Graphic pattern of the photonic crystal: 1 – quartz; 2 – polystyrene; Si – silicon

Electrons and holes concentration values are coupled with intrinsic concentration value with mass action law: $n_i^2 = np$. The intrinsic concentration value for silicon at room temperature equals $n_i = 1 \cdot 10^{10}\ \text{cm}^{-3}$. Mobility values are: $\mu_n = 1\,400\ \text{cm}^2/(\text{V}\cdot\text{s})$, $\mu_p = 500\ \text{cm}^2/(\text{V}\cdot\text{s})$. Effective masses of charge carriers $m_n^* = 0.98\, m_0$; $m_p^* = 0.49\, m_0$, where m_0 is the mass of a free electron.

For the transmission coefficient calculation the well-known transfer matrix method is used [12]. The transfer matrix for unit cell quartz/polystyrene is given by:

$$\mathbf{M} = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix}, \quad (4)$$

where

$$M_{11} = \cos(k_1 d_1)\cos(k_2 d_2) - \\ -(k_{z2}/k_{z1})\sin(k_1 d_1)\sin(k_2 d_2),$$

$$M_{12} = -i\begin{bmatrix} (1/k_{z2})\cos(k_1 d_1)\sin(k_2 d_2) + \\ +(1/k_{z1})\sin(k_1 d_1)\cos(k_2 d_2) \end{bmatrix},$$

$$M_{21} = -i\begin{bmatrix} k_{z1}\sin(k_1 d_1)\cos(k_2 d_2) + \\ +k_{z2}\cos(k_1 d_1)\sin(k_2 d_2) \end{bmatrix},$$

$$M_{22} = \cos(k_1 d_1)\cos(k_2 d_2) - \\ -(k_{z1}/k_{z2})\sin(k_1 d_1)\sin(k_2 d_2).$$

The matrix for 7 periods is given by: $\mathbf{m} = \mathbf{M}^7$.

The matrix for period quartz/silicon has the same form, but the permittivity of silicon is used instead of the permittivity of polystyrene (matrix designation – $\mathbf{M}_{\text{Si}}$).

The matrix for the whole photonic crystal is given by:

$$\mathbf{M}_{res} = \mathbf{m} \times \mathbf{M}_{\text{Si}} \times \mathbf{m}. \quad (5)$$

The transmission coefficient is determined as $T = |t|^2$, where $t = \dfrac{2}{M_{res11} + M_{res12} + M_{res21} + M_{res22}}$.

Refractive indexes are determined as $n_{1,2,\text{Si}} = \sqrt{\varepsilon_{1,2,\text{Si}}}$. The wavenumbers are determined as $k_{1,2,\text{Si}} = \sqrt{(\omega/c)^2 \varepsilon_{1,2,\text{Si}} - k_x^2}$, where c is the light velocity in vacuum, $k_x = \pi/a$, is the transverse wavenumber in which a is the length of the long wall of the waveguide.

The typical transmission spectrum of such a photonic crystal in frequency range 22…40 GHz is presented in Fig. 2. In this case, the major carriers concentration in silicon equals $p = 4 \cdot 10^{11}\ \text{cm}^{-3}$, silicon thickness is $d_{\text{Si}} = 1.45$ mm.

As it is seen in Fig. 2, the bandgap lies in frequency range, approximately, 31…38 GHz with transmission peak at 33.8 GHz frequency. The peak top according to the transmission coefficient value is 1.55 dB.

Changing the silicon layer thickness leads to a change of frequency spectrum of the PC. Herewith, the bandgap edges and the transmission peak change their frequency, but this process is not uniform for each peak. Also, as the silicon thickness increases, another transmission peak appears in the bandgap. Furthermore, the edges of the bandgap become not so obvious, the defect peak "passes" in allowed band, and becomes a peak of that band, and then, the next peak "passes" into the bandgap. Most likely, the occurrence of a second defect peak is due to the fact that the influence of two quartz layers (Fig. 1), between which the silicon is, becomes important, and which, in its turn, at some thicknesses becomes the defect mode source.

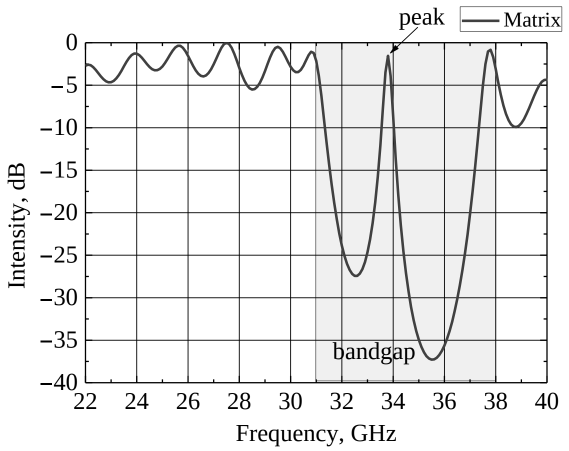

Fig. 2. Calculated transmission spectrum

In Fig. 3 the dependencies of the bandgap edges and the defect peak frequencies on thickness are presented. Plotting a graph in Fig. 3 was held under the condition of silicon layer thickness increasing from 0 to 1.5 mm (designations on the left) and, conversely, decreasing the thickness from 1.5 mm to 0 (designations on the right). It can be seen, that all lines, designated on the left, are in the lower frequency band then lines, designated on the right.

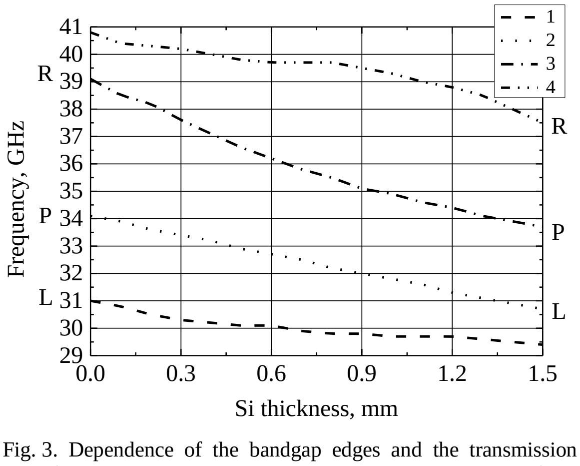

Fig. 3. Dependence of the bandgap edges and the transmission peak frequencies on silicon thickness: R is the right edge of the bandgap; L is the left edge of the bandgap; P is the transmission peak

It is seen, that peak line in Fig. 3 on the left corresponds to the peak line in Fig. 3 on the right, etc. It means that under the bandgap displacement the transmission peak "goes over" the edge and the new peak "enters" from the allowed band. Note, that a similar effect has been analyzed in [9, 13].

2. Experiment. We placed a photonic crystal from 15 unit cells (7 unit cells quartz/polystyrene, then 1 unit cell quartz/silicon, and then another 7 unit cells quartz/polystyrene) into a measuring cell (rectangular waveguide with dimensions 7.2×3.4 mm). The measuring cell is fitted to VNA Agilent PNA-L N5230 A. The measurements have been carried out in frequency range 22…40 GHz. The experimental method is described in [7].

Periodical layers of quartz and polystyrene are placed in a waveguide. The silicon disk with diameter 20 mm was stuck to the waveguide flange. The photonic crystal extension was in another waveguide without a flange. Thereby transmission of electromagnetic wave and possibility to have access to the structure are provided. The experimental equipment is presented in Fig. 4.

Fig. 4. Photo of the experimental equipment

The measurements results are presented in Fig. 5, 6.

It is seen, that the bandgap is in frequency range 31.3…37.9 GHz and the transmission peak is at 33.8 GHz frequency. Thus, we can say that the experimental results have quite good agreement with the numerical data (Fig. 2), the bandgap in the experiment is less deep than in calculations, the transmission coefficient on the defect peak equals – 8 dB. The incongruities between the experiment and the calculations are caused by, primarily, that the waveguide channel has discontinuities and small (about 1.5 mm) air gap between the silicon and the waveguide without a flange. This gap is needed for a ray of light hitting into the operating space of the silicon disk, but the presence of air gap leads to noticeable losses. The illumination has been carried out by green laser pointer with power 100 mW. The diameter of spot equals 0.6 mm. The transmission coefficient decreases by 2 dB when illuminated (Fig. 5). A bigger change was not achieved. The light influence is the most noticeable at the transmission peak, which is an expected result, because at this frequency the structure has a higher quality factor and higher sensitivity to external impacts. At the same time, the illumination does not affect the depth of the bandgap. The peak shift in frequency is also not observed.

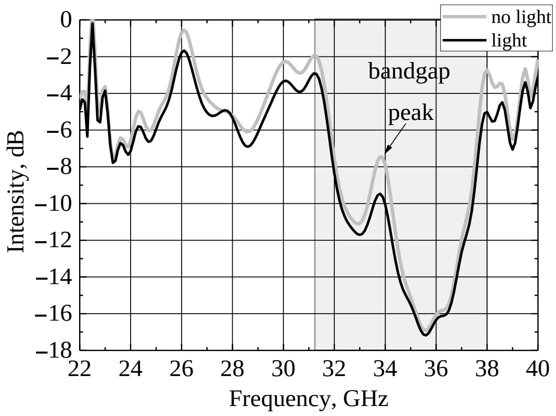

Fig. 5. Experimental spectrum of the PC with silicon layer thickness d_{Si} = 1.45 mm

Let us also consider a PC with a defective silicon layer of thickness d_{Si} = 0.5 mm.

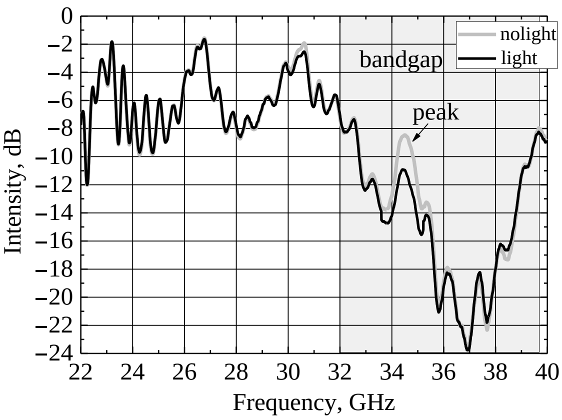

Fig. 6. Experimental spectrum of the PC with silicon layer thickness d_{Si} = 0.5 mm

The transmission peak in non-illuminated state is at 34.5 GHz frequency, transmission coefficient equals about –8.5 dB. It is less than in the previous case because the holes equilibrium concentration value in this silicon is $p = 8 \cdot 10^{11}$cm^{-3}. We have deliberately chosen silicon with non-equilibrium carriers concentration different from the previous experiment. When green light with the same intensity is illuminated, the transmission coefficient decreases to –11 dB, and the value of difference is about 2.5 dB.

3. Results and discussion. The changes in the transmission frequency spectrum of the PC are coupled with permittivity of silicon changes in the operating space under illumination. It is coupled with non-equilibrium carriers emergence which leads to photoconductivity. Illumination activates non-equilibrium carriers. In a first approximation it is possible to input non-equilibrium carriers concentration as an additive to equilibrium concentration [14]. Herewith, we suppose that the quazineutral regime is operated in the sample because the Maxwell's relaxation time is negligible. In this case, the non-equilibrium additives are equal for electrons and holes, and the space charge in the sample equals 0. Thus the equations for plasma frequencies for electrons and holes are given by:

$$\omega_{pn,p} = \sqrt{4\pi e^2 (n, p + \delta n, \delta p) \big/ m^*_{n,p} \varepsilon_p}, \qquad (6)$$

where δn, δp are non-equilibrium concentrations of electrons and holes, respectively.

We find the additive to equilibrium values of electrons and holes concentrations in formula (1), so that the transmission peak in the calculated spectrum falls by the same 2 dB, like in the experiment. This additive is $\delta n = \delta p = 1.2 \cdot 10^{13}$ cm^{-3}. In the absence of illumination the real part of silicon permittivity, calculated by the formula (1), is $\varepsilon'_{Si} = 11.8$, and the imaginary part is $\varepsilon''_{Si} = 4.373 \cdot 10^{-4}$ at the transmission peak frequency ($f_P = 33.8$ GHz). Under illumination the real part is $\varepsilon'_{Si} = 11.775$, and the imaginary part is $\varepsilon''_{Si} = 0.191$ at the same frequency. The change of the real part equals 0.025, i. e. about 0.1% and does not lead to the peak frequency shift, while a noticeable increase of the imaginary part (about 4 orders) affects the transmission coefficient value.

For quantitative description of non-equilibrium carriers role we use the continuity equations [14]:

$$\frac{dn, p}{dt} + \frac{1}{e} div J_{n,p} = G - \frac{\delta n, \delta p}{\tau_{n,p}}, \qquad (7)$$

where G is generation rate; $J_{n,p}$ are electrons and holes current densities; $\tau_{n,p}$ are non-equilibrium electrons and holes lifetimes.

As the time of experimental measurements is much more than carriers lifetime, we can consider that the system is in a stationary state, so we can neglect the change of carriers concentration in time (first term in equation (9)). Also, we consider that the light generates pairs of non-equilibrium carriers. Because of the Dember effect occurrence [15], in semiconductor subsurface layer interactive electrons and holes areas occur, and the boundary between which is meant to be p–n-junction. Further illumination leads to the occurrence of barrier-layer photo-emf, which value will be greater than Dember's emf. For taking it into account the second term in equation (9) must be non-zero. In addition, because the electrons mobility is more than holes mobility, electrons will penetrate into sample deeply and the electron area will be deeper than the hole area, which will be in the subsurface layer. Therefore, only hole area will be under illumination, but not *p–n*-junction. In it electron-hole pairs occur, but only electrons can enter the electron area because there is no potential barrier for it. Only a small part of holes can pass through this barrier into the electron area. Therefore illumination effect appears essentially in increasing minor carriers concentration, in our case – electrons [16]. In the case of uniform light absorption the generation rate G is given by the formula [14]:

$$G = \frac{\alpha \eta I}{\hbar \omega}, \tag{8}$$

where α is absorption coefficient; η is quantum efficiency (number of pairs generated by one absorbed quantum of light); I is intensity of illumination; $\hbar$ is Planck constant.

Boundary conditions for this problem are: at $x >> x_p$ $n = n_p$, $G = 0$; at $x = x_p$ $\frac{\delta n}{n} = \exp\left(\frac{eV}{kT}\right)$.

The solution of equation (7) for electrons is:

$$n - n_p - G\tau_n = \left[n - n_p - G\tau_n\right]\exp\left(-\frac{x - x_p}{L_n}\right), \tag{9}$$

where n_p is concentration of electrons in *p*-area; x_p is boundary of *p*-area; x is boundary of the illuminated area L_n is electrons diffusion length.

Using the ratio $L_{n,p} = \sqrt{D_{n,p}\tau_{n,p}}$, we obtain the solution of equation (9) for electrons and holes:

$$\begin{aligned} J_n &= \frac{eD_n n_p}{L_n}\left[\exp\left(\frac{eV}{kT}\right) - 1\right] - GeL_n, \\ J_p &= \frac{eD_p p_n}{L_p}\left[\exp\left(\frac{eV}{kT}\right) - 1\right], \end{aligned} \tag{10}$$

where k is Boltzmann constant; T is temperature; V is value of photo-emf; n_p is concentration of electrons in *p*-area; $D_{p,n} = \frac{kT}{e}\mu_{p,n}$ is the diffusion coefficient.

In the case of open circuit, the value of total current (sum of electron and hole current) equals 0. Thus, from equations (10) we obtain:

$$\left[\frac{D_p p_n}{L_p} + \frac{D_n n_p}{L_n}\right]\left[\exp\left(\frac{eV}{kT}\right) - 1\right] = GL_n. \tag{11}$$

For silicon with thickness 0.5 mm the non-equilibrium additive is $\delta n = \delta p = 1.32 \cdot 10^{14}$cm^{-3}. Herewith the permittivity value without illumination equals $\varepsilon'_{\text{Si}} = 11.8$ is the real part, and $\varepsilon''_{\text{Si}} = 2.087 \cdot 10^{-3}$ is the imaginary part. Under illumination these values are $\varepsilon'_{\text{Si}} = 11.53$, $\varepsilon''_{\text{Si}} = 2.052$. Therefore, there is a change in the real part (noticeable, but not leading to any changes in spectrum) and also in the imaginary part (by 3 orders).

From expression (13) we obtain, that if non-equilibrium concentration equals $\delta n = \delta p = 1.2 \cdot 10^{13}$ cm^{-3} the lifetime is $\tau_{n,p} = 1.14$ μs, when power equals 100 mW. When non-equilibrium concentration is $\delta n = \delta p = 1.32 \cdot 10^{14}$ cm^{-3} the lifetime equals $\tau_{n,p} = 50.5$ μs. The intensity of illumination with wavelength 532 nm in our case is $I = 0.354$ W/cm^2. The quantum efficiency for the majority of technological semiconductors is considered equal to unity. For photons with energy $E_{ph} = 2.33$ eV, corresponding to green light wavelength $\lambda = 532$ nm the absorption coefficient equals $\alpha = 10^4$cm^{-1} [17].

Conclusions. In this paper the numerical-experimental analysis of the photonic crystal quartz/polystyrene with the defect silicon layer in frequency range 22…40 GHz has been carried out.

1. The bandgap in transmission spectrum has been revealed in frequency range 31…38 GHz and the transmission peak (defect peak) at frequency 33.8 GHz (when silicon thickness is $d_{\text{Si}} = 1.45$ mm) and at frequency 34.5 GHz (when silicon thickness is $d_{\text{Si}} = 0.5$ mm). Quite a good agreement between the numerical and experimental data has been shown.

2. It is experimentally verified that the defect peak frequency strongly depends on the defect thickness (d). Thus, when d increases the defect peak "comes out" from peaks group, which form high-frequency allowed band, "comes in" into the bandgap and then "comes in" into low-frequency allowed band. Further, next peak occupies its place, which shifts by the same scenario.

3. The impact of optical radiation on the transmission coefficient at the defect peak frequency has been noticed. Non-equilibrium carriers concentration value in silicon with thickness $d_{\text{Si}} = 1.45$ mm ($\delta n = \delta p = 1.2 \cdot 10^{13}$ cm^{-3}) has been found. At this concentration the changes of the defect peak parameters in calculations and experiment coincide satisfactorily. It is shown that in this case the imaginary part of the silicon permittivity increases by 4 orders while the change in real part is negligible (about 0.1%).The same influence of the light has been detected in silicon with thickness $d_{\text{Si}} = 0.5$ mm. In this case the non-equilibrium carriers concentration value is $\delta n = \delta p =$ $= 1.32 \cdot 10^{14}$ cm^{-3}. There at the imaginary part of the

silicon permittivity increases by 3 orders while the change of the real part is negligible (about 3%).

4. In quasineutral approximation we managed to determine that non-equilibrium carriers lifetime in the illuminated area of silicon should be $\tau_{n,p} = 1.14$ μs for silicon with thickness $d_{\text{Si}} = 1.45$ mm and $\tau_{n,p} = 50.5$ μs for silicon with thickness $d_{\text{Si}} = 0.5$ mm at the parameters of illumination used in the experiment.

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МЕТОД ИЗМЕРЕНИЯ КОНЦЕНТРАЦИИ НЕРАВНОВЕСНЫХ НОСИТЕЛЕЙ ЗАРЯДА В ПОЛУПРОВОДНИКЕ И ИХ ВРЕМЕНИ ЖИЗНИ ПРИ ПОМОЩИ ФОТОННОГО КРИСТАЛЛА С ДЕФЕКТНОЙ МОДОЙ

Целью работы является экспериментальное исследование влияния свойств кремниевого дефектного слоя диэлектрического фотонного кристалла на спектральные свойства пика пропускания. Показано влияние толщины дефектного слоя на частоту дефектной моды. Продемонстрирована и проанализирована при помощи фотонного кристалла возможность изменения характеристик пика пропускания посредством облучения кремниевого слоя зеленым лазером. Экспериментально обнаружено, что облучение приводит к уменьшению величины коэффициента прохождения на частоте дефектной моды, но не изменяет частоту пика. Оценены концентрация неравновесных носителей заряда и их время жизни. Результаты данной работы могут быть использованы при производстве управляемых устройств миллиметрового диапазона длин волн и в качестве метода неразрушающего контроля свойств при производстве полупроводников.

Ключевые слова: полупроводник, фотонный кристалл, дефектный слой, неравновесные носители заряда.

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МЕТОД ВИМІРЮВАННЯ КОНЦЕНТРАЦІЇ НЕРІВНОВАЖНИХ НОСІЇВ ЗАРЯДУ В НАПІВПРОВІДНИКУ ТА ЇХ ЧАСУ ЖИТТЯ ЗА ДОПОМОГОЮ ФОТОННОГО КРИСТАЛУ З ДЕФЕКТНОЮ МОДОЮ

Метою роботи є експериментальне дослідження впливу властивостей кремнієвого дефектного шару діелектричного фотонного кристалу на спектральні властивості піку проходження. Показано вплив товщини дефектного шару на частоту дефектної моди. Показано та проаналізовано за допомогою фотонного кристалу можливість змінення характеристик піку проходження шляхом опромінення кремнієвого шару зеленим лазером. Експериментально знайдено, що опромінення призводить до зменшення коефіцієнта проходження на частоті дефектної моди, але не змінює частоту піка. Проведено чисельне оцінювання концентрації нерівноважних носіїв заряду та їх часу життя. Результати цієї роботи можуть бути використані у виробництві керованих пристроїв міліметрового діапазону довжин хвиль та в якості методу неруйнівного контролю властивостей при виробництві напівпровідників.

Ключові слова: напівпровідник, фотонний кристал, дефектний шар, нерівноважні носії заряду.