UDC 621.315.592

Radiative properties of structures with two-dimensional photonic crystals with an unprocessed central region

© A.N. Yablonskiy[1], V.E. Zakharov[1], D.V. Yurasov[1], M.V. Shaleev[1], D.V. Shengurov[1], E.E. Rodyakina[2], Zh.V. Smagina[2], A.V. Novikov[1,3]

[1] Institute for Physics of Microstructures, Russian Academy of Sciences, Nizhny Novgorod, Russia
[2] Rzhanov Institute of Semiconductor Physics, Siberian Branch, Russian Academy of Sciences, Novosibirsk, Russia
[3] Lobachevsky State University of Nizhny Novgorod, Nizhny Novgorod, Russia

E-mail: yablonsk@ipmras.ru

Received March 31, 2026
Revised May 27, 2026
Accepted May 28, 2026

Using structures with Ge(Si) nanoislands, the effect of two-dimensional photonic crystals (PhCs) with an unprocessed central region (UCR) on the luminescence properties of light-emitting semiconductor structures was studied. Using high spatial- and spectral-resolution microphotoluminescence spectroscopy, the dependence of the emission intensity and spectral characteristics on the location of the excitation region in such PhCs was investigated. A significant increase in the integral emission intensity was demonstrated upon excitation of charge carriers at the center of the UCR compared to excitation in the periodic region of the PhC. A study of the PL spectra of PhCs with various parameters revealed that this increase is due to the efficient extraction of emission near the boundary of the UCR and the periodic region of the PhC due to its interaction with PhC modes. It was found that the maximum gain in the integral emission intensity of PhCs with UCR compared to spatially uniform PhCs is observed at low optical excitation levels, which is associated with a higher concentration of nonradiative recombination centers in the uniform PhCs. At the same time, at high optical pumping levels, due to the partial saturation of nonradiative recombination centers and the effective interaction of the emission from Ge(Si) islands with high-Q modes of the PhCs, the emission intensity of the uniform PhCs at wavelengths corresponding to these modes can significantly exceed the emission intensity of PhCs with UCR. The obtained results can be used for the development of near-IR radiation sources for silicon-based photonic integrated circuits..

Keywords: Ge(Si) nanoislands, two-dimensional photonic crystals, microphotoluminescence spectroscopy, nonradiative recombination, bound states in the continuum (BIC).

DOI: 10.61011/SC.2026.02.63742.9459

1. Introduction

Today one of the promising areas of studies in the field of photonics is the increase of efficiency of light emitting semiconductor structures through the use of 2D photonic crystals (PhC) [1–5]. PhC formation on structures with self-assembled Ge(Si)-nanoislands grown on the „silicon-on-iinsulator“ (SOI) substrates is of special interest [4–7], since such structures are well-compatible with the current silicon integral technology [8,9], radiate in the telecommunications spectral range of $1.3-1.6\,\mu$m [10–12] at room temperature and may therefore be used to design the radiation sources for silicon photonics. Formation of PhC enables significant improvement of radiation exit from semiconductor structures [1,3,13], and effective control of the active medium radiation spectrum type, since the increase in the luminescence intensity in structures with PhC is observed only at certain wavelengths, corresponding to PhC modes and depending on PhC parameters, such as period, radius, depth of PhC holes etc. [3–7,14–16]. At certain PhC parameters in photoluminescence (PL) spectra, very narrow lines may be observed (with the width of < 1 meV), provided for by the implementation of so called „bound states in the continuum“ (BIC) in the PhC [17–21]. It is necessary to note that for the structures with Ge(Si)-islands the increase in the intensity of radiation in PhC was demonstrated under the conditions of both optical and electric excitation. The latter was achieved by formation of lateral p^+-i-n^+-light diodes with 2D PhCs built into i-region of the diodes on the SOI substrates [22–24].

Despite the specified advantages of the structures with PhC, their practical use is complicated by a few significant disadvantages related to their design and manufacturing technology. First of all, formation of PhC by plasma chemical etching method [25,26] is accompanied with the generation of defects on the walls of PhC holes, which together with the increase in the total surface area of the structure becomes the reason for the significant increase in the rate of nonradiative recombination of the charge carriers in the PhC region [27]. Partially this problem may be

solved by passivation of the PhC surface [28]. Second, etching of the PhC holes causes removal of a part of the active medium, where the radiative recombination of the charge carriers takes place. Finally, for the structures with the electric pumping (for example, lateral light diodes) on SOI substrates the PhC formation results in drastic drop of current through the structure [22,23], which also reduces the radiative effectiveness of the produced structures.

The solution that allows to a significant degree to eliminate the listed disadvantahes of the 2D PhCs may be the formation of the PhC with an unprocessed central region (UCR) — a region of initial structure without holes, which is surrounded with a periodical PhC from all sides [2,13]. Previously, using the example of structures with Ge(Si)-islands it was shown [29] that in PhC with UCR the excitation of islands located in this region may lead to a considerable (several times) increase of the PL intensity in the islands compared to the PhC that are uniform in the surface area (PhC without UCR). The studies of spectral and time characteristics of PL in Ge(Si)-islands of PhCs of various type showed that the observed benefit in the PL intensity of PhC with UCR compared to uniform PhCs is related to the absence of additional nonradiative recombination in the UCR provided for by the formation of PhC [29]. Besides, the question of the main mechanism of PL intensity rise in PhC with UCR compared to initial planar structures remained open, since the PL spectra of such PhCs demonstrated significant differences from the PL spectra of the PhCs that are uniform in the surface area with the similar parameters, in particular, absence of intensive narrow lines connected to most high quality BIC modes of PhCs. In paper [29] an assumption was made that the main mechanism of PL intensity rise in PhCs with UCR and in uniform PhCs was the increase of radiation yield efficiency due to the interaction of the latter with the PhC modes. In this case the type of PL spectra of PhCs with UCR must be defined by the mode structure of PhC surrounding the unprocessed region. At the same time it is necessary to consider that the features observed in the PL spectra of PhCs with UCR may be related both to the PhC modes and to the resonant effects provided for by the geometry of the UCR itself, since this region, being a section of the initial planar structure, surrounded from all sides with the periodical PhC with a lower average dielectric permeability, may itself act as an optical resonant cavity. Therefore, the PL spectrum of Ge(Si)-islands located in the UCR may, as a matter of principle, be contributed by Fabry–Perot modes or whispering gallery modes generated by multiple reflection of the radiation from the interface of UCR and external, periodical part of PhC.

To determine the main mechanism of PL intensity rise in Ge(Si)-islands in PhC with UCR, and also to establish the causes for the substantial difference in the type of PL spectra of PhC with UCR and PhCs homonegeous in their surface area, this paper analyzed the PL spectra of the PhCs with UCR under local excitation of various fields such as PhC using the micro-PL spectroscopy method providing for high spatial and spectral resolution. To identify the contribution of the nonradiative recombination, comparative studies were also conducted on the dependences of PL intensity of uniform PhCs and PhCs with UCR on the power of the optical excitation.

2. Experimental method

A structure with five layers of Ge(Si)-nanoislands separated with Si layers was grown by the method of molecular beam epitaxy at 600 °C on the SOI substrate with the buried layer SiO_2 with thickness of $2\,\mu$m [15,30]. The total thickness of the structure above the buried layer SiO_2 (including buffer and coating layers of Si) was 335 nm. 2D PhCs with a hexagonal lattice were made by methods of electron beam lithography and plasma chemical etching [15,30]. PhC parameters (period a, radius of holes r and depth of hole etching, which was 250 nm) were selected with the account of the results of the previous studies [14,27,31] to achieve the maximum intensity of the PL signal. The lateral dimensions of the PhCs were $50 \times 50\,\mu$m. For each set of the parameters (a and r) the PhCs that were uniform in their surface area and the PhCs with the unprocessed central region (UCR) with diameter of $20\,\mu$m were formed [29].

The studies of luminescent properties of structures with PhCs were conducted using micro-PL spectroscopy method in the near IR range at room temperature [16,29]. PL was excited by continuous laser radiation with wavelength of 532 nm, which focused on the sample surface using Mitutoyo Plan APO NIR objectives with magnification of $20\times$ and $50\times$. When the specified objectives were used, the excitation spot size was $1-2\,\mu$m, which provided for the high spatial resolution necessary for local excitation of various regions in the studied PhCs. The radiation was collected using the same objective that was used to focus the laser radiation. The sample with PhCs was located on a two-stage linear translator, which made it possible to move the excitation spot along the sample surface relative to the elements of the structure and to study the change in the PL spectra under local excitation of various PhC regions. The PL signal was recorded using a Fourier spectrometer Bruker IFS 125 HR (with spectral resolution of up to 0.1 meV) and a Ge-photodetector cooled with liquid nitrogen.

3. Experimental results and discussion

To analyze the effect of PhCs with UCR on the radiative properties of structures with Ge(Si)-nanoislands, the PL spectra of such PhCs were studied with the high spatial resolution, which was achieved by reduction of the excitation region size to $1\,\mu$m when the exciting radiation was focused using the objective $50\times$. This made it possible to track the change in intensity and shape of PL spectra with a shift of the excitation region of charge carriers in the PhC with UCR from the center of the unprocessed

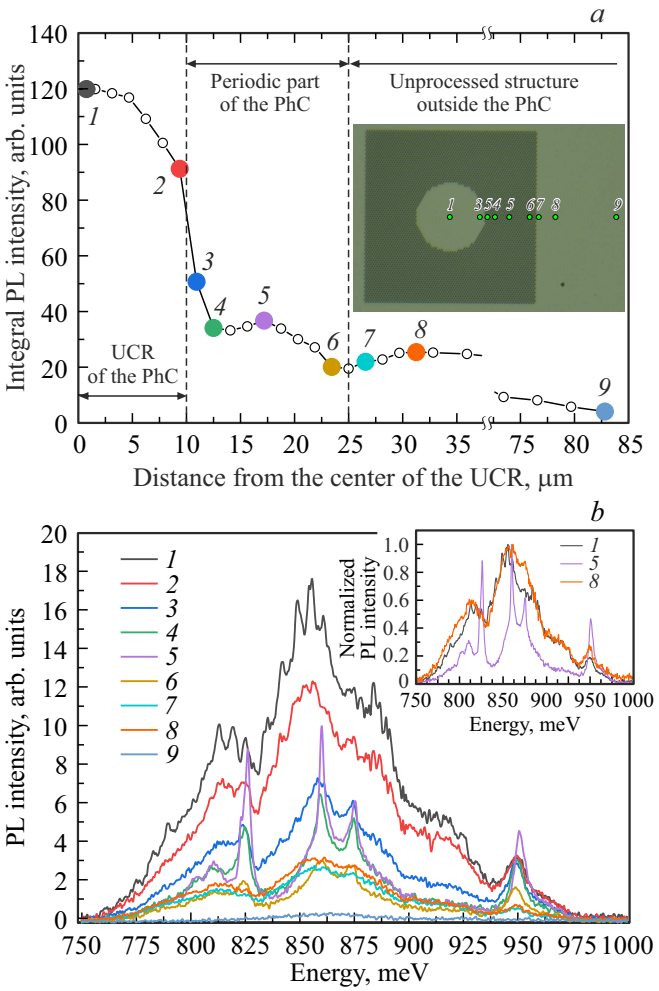

Figure 1. *a* — dependence of integral intensity of PL from Ge(Si)-islands in the PhC with the unprocessed central region (UCR) ($a = 670$ nm, $r/a = 0.33$) on the position of the excitation region of the charge carriers at pumping power of 3 mW. The dotted lines specify the boundary between the UCR and the periodical region of PhC and the external boundary of PhC located at the distance of 10 and 25 μm from the PhC center accordingly. On the insert — positions of the excitation spot corresponding to the values of PL intensity marked in Figure 1. *b* — PL spectra of PhCs with UCR under excitstion in the points specified in Figure 1, *a*. On the insert — normalized PL spectra under excitation in the UCR center (point *1*), in the middle of the periodical region of PhC (point *5*) and outside the PhC near its outer boundary (point *8*).

region to the outer boundary of PhC, as shown on the insert to Figure 1, *a*. The PL signal was recorded from the entire surface area of the studied PhC. Figure 1, *a* shows the dependence of the integral intensity of PL in PhCs with UCR on the distance from the center of PhC measured at the optical pumping power of 3 mW. The experimental values of PL intensity were obtained by integration of the PL spectra measured at a different distance from the UCR center in the entire spectral range of radiation of Ge(Si)-islands (750–1000 meV). Figure 1, *b* presents the corresponding PL spectra obtained under excitation in the points specified on the insert to Figure 1, *a*. Dotted lines in Figure 1, *a* specify the internal boundary of PhC with UCR (boundary between the UCR and the periodical region of PhC) and the external boundary of PhC located accordingly at the distance of 10 and 25 μm from the PhC center.

From Figure 1, *a* you can see that the integral intensity of PL in the PhCs with UCR takes maximum values under excitation near the UCR center (point *1*) and monotonously decreases when the excitation spot approaches the boundary of the UCR with the processed periodical region of PhC. Seemingly, this is explained by the fact that the maximum distance between the UCR center and the holes that form the PhCs provides for the least influence of additional centers of nonradiative recombination, related to the formation of PhCs, i. e. the highest probability of radiative recombination in Ge(Si)-islands available in this PhC region. As it was shown in paper [29], the specific times of charge carrier lives in the UCR exceed the life times in the processed region of the PhC several times and are close to the life time in the initial planar structure without the PhC. Besides, most radiation arising as a result of recombination of the charge carriers in Ge(Si)-islands located in the UCR, spread in the upper waveguide layer of the structure, is effectively backlit from the structure on the inner boundary of the periodical (processed) PhC region thst surrounds the UCR.

As you can see in Figure 1, *b*, when the PL excitation region is located inside the UCR, and also in the periodical region of the PhC in close proximity to the boundary with UCR (points *1–3* in Figure 1, *a* and spectra *1–3* in Figure 1, *b*) the shape of the PL spectra remains practically unchanged. The spectra show some features, which, as it was specified above, may be related both to the modes of the PhC surrounding the UCR and to the Fabry–Perot modes or whispering gallery modes, which may be generated under multiple reflection of radiation from the interface of the UCR and the outer periodical part of the PhC. Further it will be shown that namely the mode structure of the periodical PhC surrounding the UCR is decisive in the formation of the PL spectrum of the Ge(Si)-islands in the UCR. The drop in the integral intensity of PL when the excitation spot moves from the UCR center to the region with the PhC holes is seemingly related to the diffusion of some non-equilibrium charge carriers to the periodical region of the PhC and, accordingly, to the increase in the contribution of the surface nonradiative recombination on the side walls of the PhC holes. When the excitation spot moves directly into the region with the PhC holes (points *3–6* in Figure 1, *a*), this contribution becomes maximal, which causes the drop in the integral intensity of PL 3–5 times compared to the case of the PL excitation in the UCR center. Simultaneously the noticeable change is observed in the shape of the PL spectrum, which manifests itself as a series of narrow intensive lines. In this case, the PL spectrum of the PhCs with UCR becomes practically identical to the PL spectrum of the periodical PhC uniform

in the surface area with similar parameters (period a, hole radius r etc.). This indicates that narrow intensive lines arising in the PL spectrum of the PhC with UCR when excited in the region with PhC holes (points *4–6* in Figure 1, *a*) are related to high Q BIC modes specific for uniform 2D PhCs [7,16,17]. Comparison of the PL spectra measured under local excitation of various sections of PhCs with UCR shows that the maximum intensity of the PL lines related to high Q BIC modes of PhC, is observed under excitation of charge carriers in the region containing PhC holes, and at the same time located at a sufficient distance from the PhC boundaries with the unprocessed region of the structure. As the excitation spot approaches the inner or outer boundary of PhC, the intensity of the specified high Q lines drops noticeably, and when the excitation spot moves to the unprocessed region of the structure (inside or outside the PhC), they completely disappear. This result confirms that the necessary condition for the formation of high Q BIC modes in the 2D PhCs is the possibility to spread the radiation of the active medium in the periodical structure of the PhC from the PL excitation region in all directions in the plane of the structure growth. This condition is only met for excitation in the PhC region located inside the array of the PhC holes, further from its boundaries (both outer and inner ones). Previously in some papers [17,20] it was shown that the formation of the high Q BIC modes significantly depends on the lateral dimensions, i.e. on the number of periods of the PhC lattice. For the PhCs with UCR when the excitation region is located inside the UCR, the radiation enters the periodical region of PhC only from one direction (through the boundary with UCR). Such configuration provides only excitation of low Q „radiative“ modes, to generate which, several PhC periods are enough, but does not meet the conditions necessary to form the high Q BIC modes requiring spread of radiation in the large surface area of the 2D periodical structure comparable to the full size of formed PhCs.

As the PL excitation region moves to the unprocessed region of the structure beyond the limits of the PhC outer boundary (points *7–8* in Figure 1, *a*), a certain increase is observed again in the integral PL intensity (compare points *6* and *8* in Figure 1, *a*), which, as in the case of excitation inside the UCR, is related to the decreased contribution of nonradiative recombination of charge carriers in the region free from PhC holes. Note that PL intensity with the excitation region located beyond the PhC is expectedly lower (4–6 times) versus PL excitation inside the UCR, since in this case only a small proportion of radiation from Ge(Si)-islands spreads in the direction of PhC and is efficiently extracted from the studied structure. Despite this, even under excitation beyond PhC (next to its outer boundary), the PL intensity is almost an order higher than the PL intensity of the initial planar structure far from PhC (point *9* in Figure 1, *a*).

The convincing confirmation of the fact that the main mechanism of PL intensity increase in PhCs with UCR compared to the initial planar structures, as in uniform PhCs,

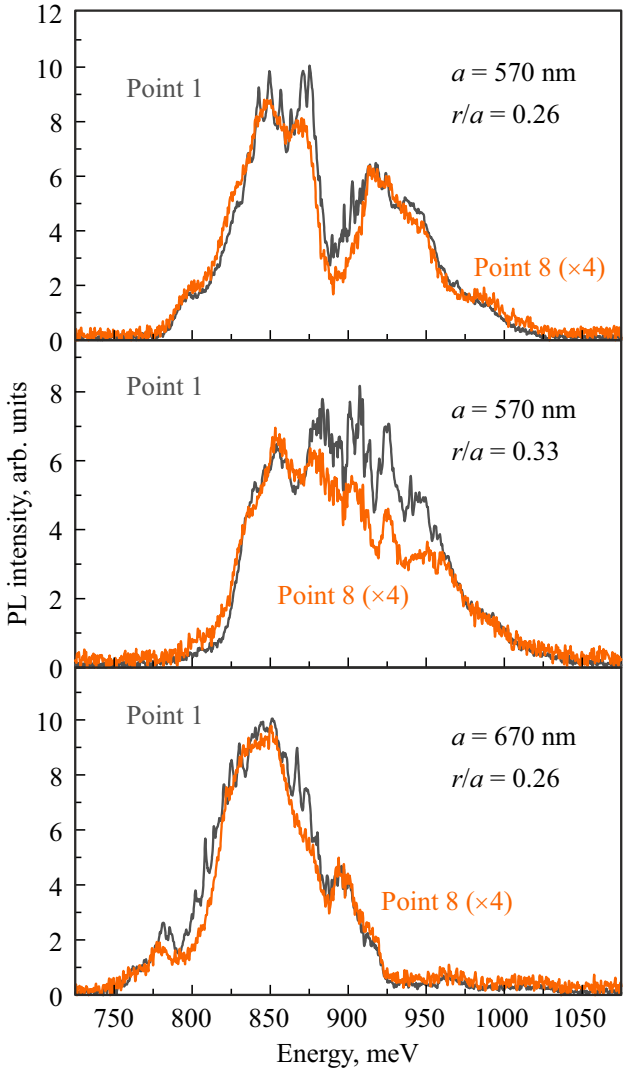

Figure 2. The PL spectra of Ge(Si)-islands in the PhCs with UCR with different parameters (period a and radius of holes r), measured under excitation in the UCR center (point *1* in Figure 1, *a*) and beyond the PhC, near its outer boundary (point *8* in Figure 1, *a*) at pumping power of 3 mW.

is the effective extraction of radiation at the wavelengths corresponding to PhC modes, are the results of the comparative analysis of the PL spectra obtained under excitation inside UCR and beyond PhC, next to its outer boundary (points *1* and *8* in Figure 1, *a*). The insert to Figure 1, *b* shows PL spectra of PhCs with UCR, normalized by the maximum value of the intensity measured in the center of UCR (point *1*), in the middle of the periodical region of the PhC (point *5*) and beyond the PhC near its outer boundary (point *8*). As you can see from the figure, the PL spectra measured inside the UCR and beyond the PhC are practically identical, and all main features observed under PL excitation in the UCR are also present in the spectra obtained under excitation near the outer boundary of the PhC.

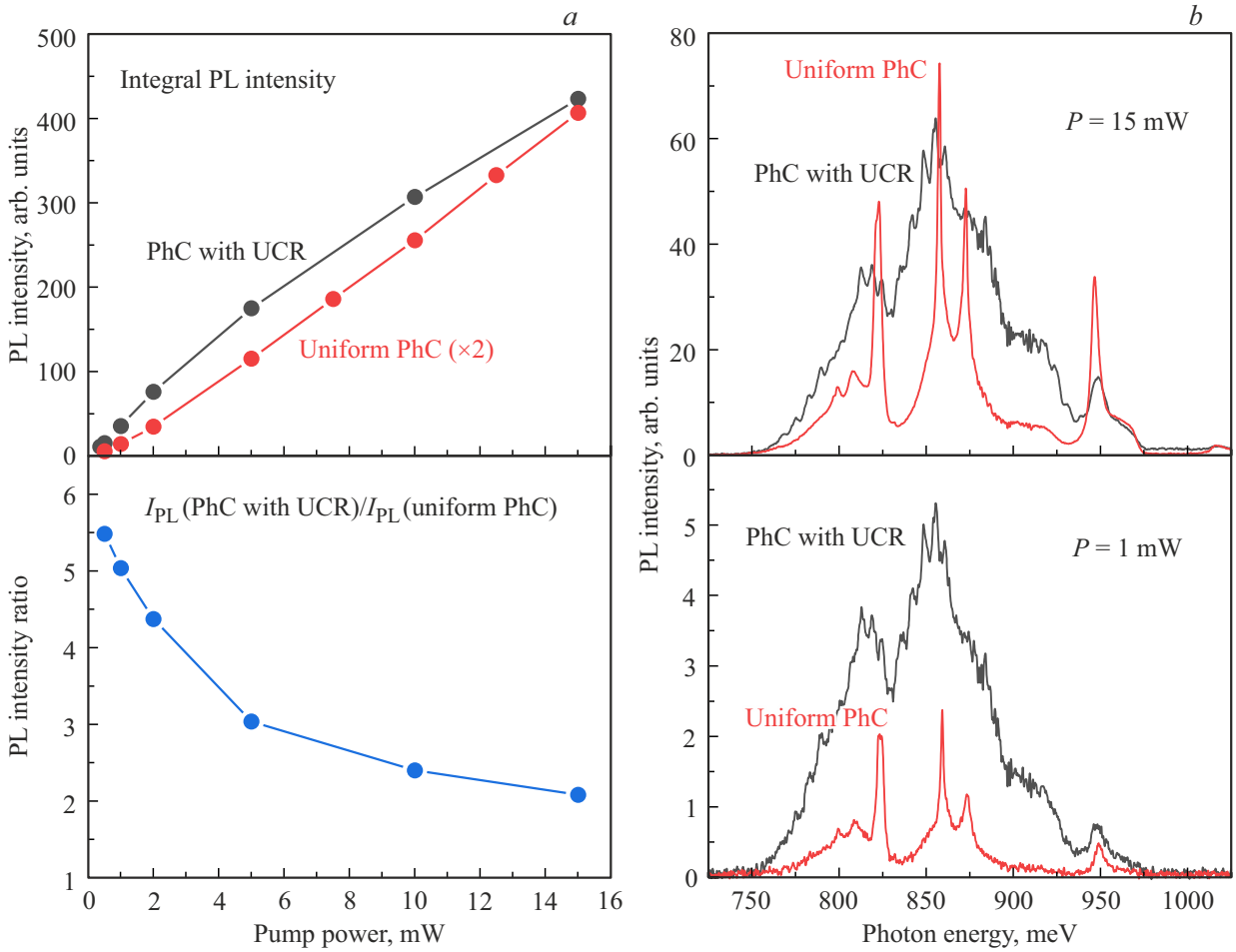

Figure 3. *a* — integral PL intensities of uniform PhC and PhC with UCR and their ratio as a function of optical pumping power. *b* — PL spectra of uniform PhC and PhC with UCR at excitation power values of 15 and 1 mW. The data are given for the PhCs with $a = 670$ nm and $r/a = 0.33$.

As the additional test for this result, the PL spectra measured in points *1* and *8* were compared for several PhCs with UCR with other parameters a and r/a (Figure 2). As you can see from Figure 2, the shape of PL spectra in PhCs with UCR in both cases of excitation is practically the same and is determined exclusively by PhC parameters. This result indicates that the observed spectral features are related specifically to the mode structure of PhC, and not to the geometric shape or the size of the UCR itself. As it was specified earlier, the PL intensity with the excitation region located inside the UCR is significantly (4–6 times) higher than under PL excitation beyond the PhC limits, since in the first case the excitation region is surrounded from all sides with the periodical structure of the PhC, and the radiation excited in the UCR is effectively extracted from the structure along the entire perimeter of the UCR, whereas in the second case only a small proportion of the radiation spreads in the PhC direction and is efficiently extracted from the structure.

It should be noted that the win in the integral PL intensity of the PhCs with UCR compared to the uniform periodical PhCs is not a constant value and may vary substantially, for example, with the variation of the optical pump power (Figure 3). As shown in Figure 3, *a*, the integral PL intensity of uniform PhCs and PhCs with UCR demonstrates different dependence on the pumping power under excitation of the charge carriers in the PhC center, which is caused by significant difference in the concentrations of the centers of nonradiative recombination in the region of photoexcitation in these two types of PhCs. At low pumping power (≤ 1 mW) the integral PL intensity in PhCs with UCR is more than 5 times higher than the PL intensity of the uniform PhC. Such significant difference is explained by the fact that in the uniform PhC the excitation of the charge carriers is carried out in the region with the holes of the PhCs, at the boundaries of which the intensive nonradiative recombination of the charge carriers is taking place. At the same time in the PhCs with UCR the charge carriers are generated in the region without the PhC holes, in which the rate of nonradiative recombination is substantially lower. In paper [29] it was confirmed by comparative study of PL kinetics in different types of PhCs.

As the excitation power increases, centers of nonradiative recombination are partially saturated in the uniform PhC, which results in the increased proportion of the charge carriers that recombine radiatively, and, therefore, to faster growth of PL intensity in this type of PhC compared to PhC with UCR. As a result of this effect, the ratio of integral PL intensities in the PhCs with UCR and in the uniform PhC decreases significantly with the increase of the pumping power and is around 2 times at the excitation power of 15 mW (Figure 3, *a*). It should be noted that at high excitation levels, the peak PL intensity in uniform PhCs at the wavelengths corresponding to the high Q BIC modes of PhC [29] may noticeably exceed the PL intensity in the PhC with UCR (Figure 3, *b*). Therefore, the maximum win in the PL intensity of PhC with UCR related to the absence of the additional nonradiative recombination of charge carriers shows itself mainly at low levels of excitation, whereas at high pumping levels, under the conditions of partial saturation of nonradiative recombination channels, the use of PhCs uniform in the surface area may turn out to be more effective for the increase of the PL intensity at fixed wavelengths, including at the expense of generation of high Q modes of PhCs.

With account of the above advantages of the 2D PhCs with UCR, one of the possible applications of such PhCs may be their use for improvement of efficiency of lateral light-emitting p^+-i-n^+-diodes. Previously for the lateral p^+-i-n^+-diodes with Ge(Si)-islands grown on a SOI substrate, it was shown that formation of 2D PhCs in the *i*-region of such diodes makes it possible to substantially increase the intensity of their radiation, and also to control the shape of the EL spectrum [22–24]. One of the main disadvantages of such light diodes is sharp drop of current through the diode, when the PhC is formed in the *i*-region of the diode. It is natural to assume that the use of the PhC with the unprocessed central region combined with the *i*-region of p^+-i-n^+-diodes will make it possible to significantly increase the value of the current passing through the diode, and to significantly decrease the contribution of nonradiative recombination, which will result in the increase of the efficiency of such light diodes.

4. Conclusion

The paper compared the intensity and shape of PL spectra of PhCs with the unprocessed central region (UCR) depending on the position of the excitation spot and the density of the optical pumping power. It is shown that the maximum integral PL intensity in such PhCs is achieved under PL excitation near the center of the UCR, which is due to the minimization of the nonradiative recombination of the charge carriers related to the PhC formation and the efficient extraction of radiation through the UCR boundary with the periodical structure of the PhC. At the same time the ratio of integral PL intensities of the PhCs with UCR and PhCs that are uniform in the surface area significantly depends on the level of optical pumping due to the presence of additional centers of nonradiative recombination in uniform PhCs. It is established that the shape of the PL spectrum of the PhCs with UCR depends on the mode structure of the PhC and is not related to the parameters of the UCR as such. The main difference of the PL spectra of the PhCs that are uniform in the surface area and PhCs with UCR consists in the absence of the narrowest and most intensive lines in the second type PhCs, with these lines being related to high Q BIC modes of PhCs, the necessary condition to form which is the possibility to spread the radiation of the active medium in the periodical structure of the PhC from the excitation region in all directions in the structure growth plane. The obtained results may be used for the development of the sources of near IR radiation for the photonic integrated cirquits based on silicon, in particular, to increase the radiative efficiency of lateral p^+-i-n^+-light diodes with 2D PhCs.

Funding

The studied structures with photonic crystals were produced under the state assignment of the Institure of Physics of Microstructures of the Russian Academy of Sciences (FFUF-2024-0019). The luminescent measurements were carried out under the grant of the Russian Scientific Foundation No. 25-12-00367 using the equipment of the Common Use Center „Physics and Technology of Micro- and Nanostructures“ of the Institute of Physics of Microstructures of the Russian Academy of Sciences.

Conflict of interest

Authors declare no conflict of interest.

References

[1] S. Fan, P.R. Villeneuve, J.D. Joannopoulos, E.F. Schubert. Phys. Rev. Lett., **78**, 3294 (1997).
[2] M. Boroditsky, R. Vrijen, T.F. Krauss, R. Coccioli, R. Bhat, E. Yablonovitch. J. Lightwave Technol., **17**, 2096 (1999).
[3] A. Mahdavi, G. Sarau, J. Xavier, T.K. Paraiso, S. Christiansen, F. Vollmer. Sci. Rep., **6**, 25135 (2016).
[4] S. David, M. El kurdi, P. Boucaud, A. Chelnokov, V. Le Thanh, D. Bouchier, J.-M. Lourtioz. Appl. Phys. Lett., **83**, 2509 (2003).
[5] R. Jannesari, M. Schatzl, F. Hackl, M. Glaser, K. Hingerl, T. Fromherz, F. Schäffler. Opt. Express, **22**, 25426 (2014).
[6] M.V. Stepikhova, A.V. Novikov, A.N. Yablonskiy, M.V. Shaleev, D.E. Utkin, V.V. Rutckaia, E.V. Skorokhodov, S.M. Sergeev, D.V. Yurasov, Z.F. Krasilnik. Semicond. Sci. Technol., **34**, 024003 (2019).
[7] S.A. Dyakov, M.V. Stepikhova, A.A. Bogdanov, A.V. Novikov, D.V. Yurasov, M.V. Shaleev, Z.F. Krasilnik, S.G. Tikhodeev, N.A. Gippius. Laser Photon. Rev., **15**, 2000242 (2021).
[8] S. Saito, A. Al-Attili, K. Oda, Y. Ishikawa. Semicond. Sci. Technol., **31**, 043002 (2016).

[9] V. Reboud, A. Gassenq, J. Hartmann, J. Widiez, L. Virot, J. Aubin, K. Guilloy, S. Tardif, J. Fedeli, N. Pauc, A. Chelnokov, V. Calvo. Progr. Cryst. Growth Char. Mat., **63**, 1 (2017).
[10] L. Vescan, T. Stoica, O. Chretien, M. Goryll, E. Mateeva, A. Muck. J. Appl. Phys., **87**, 7275 (2000).
[11] Yu.N. Drozdov, Z.F. Krasilnik, K.E. Kudryavtsev, D.N. Lobanov, A.V. Novikov, M.V. Shaleev, D.V. Shengurov, V.B. Shmagin, A.N. Yablonskiy. Thin Sol. Films, **517**, 398 (2008).
[12] Z.F. Krasilnik, A.V. Novikov, D.N. Lobanov, K.E. Kudryavtsev, A.V. Antonov, S.V. Obolenskiy, N.D. Zakharov, P. Werner. Semicond. Sci. Technol., **26**, 014029 (2011).
[13] M. Boroditsky, T.F. Krauss, R. Coccioli, R. Vrijen, R. Bhat, E. Yablonovitch. Appl. Phys. Lett., **75**, 1036 (1999).
[14] A.N. Yablonsky, A.V. Novikov, M.V. Stepikhova, S.M. Sergeev, N.A. Baydakova, M.V. Shaleev, Z.F. Krasilnik. FTP, **54**, 1150 (2020) (in Russian).
[15] D.V. Yurasov, A.N. Yablonsky, M.V. Shaleev, D.V. Shengurov, E.E. Rodyakina, Zh.V. Smagina, V.A. Verbus, A.V. Novikov. Pisma ZhTF, **49**, 29 (2023) (in Russian).
[16] A.V. Peretokin, D.V. Yurasov, M.V. Stepikhova, M.V. Shaleev, A.N. Yablonskiy, D.V. Shengurov, S.A. Dyakov, E.E. Rodyakina, Zh.V. Smagina, A.V. Novikov. Nanomaterials, **13**, 1678 (2023).
[17] A. Kodigala, T. Lepetit, Q. Gu, B. Bahari, Y. Fainman, B. Kanté. Nature, **541**, 196 (2017).
[18] N.D. Le, P. Bouteyre, A. Kheir-Aldine, F. Dubois, S. Cueff, L. Berguiga, X. Letartre, P. Viktorovitch, T. Benyatou, H.S. Nguyen. Phys. Rev. Lett., **132** (17), 173802 (2024).
[19] D.V. Yurasov, S.A. Dyakov, I.A. Smagin, S.G. Tikhodeev, N.A. Gippius, M.V. Stepikhova, A.V. Peretokin, M.V. Shaleev, Zh.V. Smagina, D.E. Utkin, A.V. Novikov. Appl. Phys. Lett., **125**, 021105 (2024).
[20] R. Hao, B. Ye, J. Xu, Y. Zou. Front. Optoelectron., **18**, 3 (2025).
[21] A.V. Peretokin, M.V. Stepikhova, A.N. Yablonskiy, M.V. Shaleev, S.A. Dyakov, N.A. Gippius, A.V. Novikov. J. Appl. Phys., **138**, 123105 (2025).
[22] V.B. Shmagin, A.V. Novikov, A.N. Yablonsky, M.V. Stepikhova, D.V. Yurasov, A.N. Mikhaylov, D.I. Tetelbaum, E.E. Rodyakina, E.E. Morozova, D.V. Shengurov, S.A. Kraev, P.A. Yunin, M.V. Shaleev, A.I. Belov. ZhTF, **49**, 12 (2023) (in Russian).
[23] V.B. Shmagin, A.N. Yablonskiy, M.V. Stepikhova, D.V. Yurasov, A.N. Mikhaylov, D.I. Tetelbaum, E.E. Rodyakina, E.E. Morozova, D.V. Shengurov, S.A. Kraev, P.A. Yunin, A.I. Belov, A.V. Novikov. Nanotechnology, **35**, 165203 (2024).
[24] A.N. Yablonskiy, V.B. Shmagin, V.E. Zakharov, D.V. Yurasov, M.V. Shaleev, E.V. Demidov, A.N. Mikhaylov, D.I. Tetelbaum, E.E. Rodyakina, E.E. Morozova, D.V. Shengurov, S.A. Kraev, A.V. Novikov. Appl. Phys. Lett., **125**, 231103 (2024).
[25] A. Clarke, M. Darnon, K. Hinzer, M. de Lafontaine. Micro Nano Eng., 100330 (2025).
[26] D.V. Yurasov, M.V. Shaleev, D.V. Shengurov, A.V. Peretokin, E.V. Skorokhodov, E.E. Rodyakina, Zh.V. Smagina, A.V. Novikov. ZhTF, **95**, 128 (2025) (in Russian).
[27] A.N. Yablonsky, D.V. Yurasov, V.E. Zakharov, A.V. Peretokin, M.V. Stepikhova, M.V. Shaleev, D.V. Shengurov, E.E. Rodyakina, Zh.V. Smagina, A.V. Novikov. Opticheskiy zhurn., **91**, 50 (2024) (in Russian).
[28] H. Kim, B.-S. Song, S. Noda, T. Asano. J. Opt. Soc. Am. B, **42** (10), 2358 (2025).
[29] A.N. Yablonskiy, V.E. Zakharov, D.V. Yurasov, M.V. Shaleev, D.V. Shengurov, V.B. Shmagin, E.E. Rodyakina, Zh.V. Smagina, A.V. Novikov. Appl. Phys. Lett., **128**, 031103 (2026).
[30] A.N. Yablonsky, D.V. Yurasov, V.E. Zakharov, A.V. Peretokin, M.V. Stepikhova, M.V. Shaleev, D.V. Shengurov, E.E. Rodyakina, Zh.V. Smagina, S.A. Dyakov, A.V. Novikov. FTP, **57**, 251 (2023) (in Russian).
[31] M.V. Stepikhova, S.A. Dyakov, A.V. Peretokin, M.V. Shaleev, E.E. Rodyakina, A.V. Novikov. Nanomaterials, **12**, 2687 (2022).

Translated by M.Verenikina