Enhancement of the luminescence response of subwavelength lattices of Si disks with embedded GeSi quantum dots when switching from a simple lattice to a lattice with a basis

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The effect of the lattice basis modification of photonic crystal on the luminescence properties of emitters embedded in them was studied. The photonic crystals were square lattices of subwavelength Si disks with embedded GeSi quantum dots. The basis was modified by changing the size of the disks in one of the sublattices with a doubled period. A microphotoluminescence study revealed that this change in the photonic crystal structure leads to a multiple increase in the intensity of individual photoluminescence peaks in the emission region of the GeSi quantum dots. A theoretical calculation of the emissivity of the studied structures confirms that the observed effect is based on an increase in the local density of optical states in the modified structure.

Keywords: luminescence, quantum dots, photonic crystal, bound states in the continuum.

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1. Introduction

Currently, significant progress is being made in the application of photonic crystals (PC) and metasurfaces for the development of various photonic devices (lasers, photodetectors, waveguides, and other elements necessary for building optical communication and information processing circuits) operating in the telecommunications range [1–9]. In such systems, high-quotient states with very low radiation losses can be observed, tending to zero in the limit [1,2,4–7], which are commonly referred to as bound states in a continuum (BSC).

There are two main types of BSC. The first type of BSC is due to the prohibition of radiation into the far field due to the mismatch of symmetry of photonic states (eigenmodes) inside the periodic structure and modes propagating in free space. This type of BSC is commonly referred to as symmetrically protected. The second type of CSC is realized under certain system parameters (for example, at a certain angle of incidence of light), when destructive interference of resonances occurs, leading to the formation of „dark“ (non-emitting) states. Lowering the symmetry of the eigenmodes of the PC can weaken the ban on radiation into the far field and thus strongly modify the spectral characteristics of the radiation coming out of the structure. It was shown in Ref. [6,8–10] that a change in the symmetry of PC due to lattice deformation or modification of the shape of the constituent elements of PC strongly changes the band structure of PC, leading to the removal of degeneracy and the opening of forbidden zones. It was demonstrated in Ref. [6] that such changes in the PC structure lead to an increase in the intensity of photoluminescence at certain wavelengths. In theoretical studies for PC [9,10], which are square lattices made of dielectric cylinders, it was found that modification of the PC structure by changing the size of the cylinders in two sublattices that make up a photonic crystal leads to the removal of band degeneracy and the discovery of new photonic bandgaps that are absent in the structure of identical cylinders. When moving from a lattice of identical cylinders to a structure of two sublattices with cylinders of different sizes, only half of all the symmetry elements of the spatial group remain, namely, only those elements that do not swap the two sublattices. It can be assumed that such a modification of the PC structure will have a significant impact on the radiative properties of the system.

This paper studied photonic crystals which are subwavelength square lattices made of Si disks with GeSi quantum dots embedded in them. Experimental and theoretical studies of the effect of modification of the lattice basis of a photonic crystal by changing the diameter of disks in one of the sublattices on the luminescent properties of embedded radiators have been carried out.

2. Experimental procedure

The growth of structures with GeSi quantum dots (QD) was performed on a silicon-on-insulator substrate with a 240 nm thick upper Si layer and a $3\,\mu$m thick SiO_2 sublayer. A 110 nm thick Si buffer layer was grown on this substrate by molecular beam epitaxy at 500 °C at a rate of 0.6 Å/s. Further, 10 layers of GeSi QD separated by silicon layers with a thickness of 15 nm were grown at a temperature of 600 °C. Each QD layer was formed by deposition of 7 Ge monolayers with a growth rate of 0.15 Å/s. The growth of the structures ended with the deposition of a 20 nm thick covering layer of Si. The separation and cover layers of Si were grown at a rate of 0.6 Å/s. The total thickness of the multilayer structures was 480 nm.

The formation of photonic crystals on the grown structures involved several stages. At the first stage, a metal mask was formed using electron lithography, magnetron deposition of a chromium film, and explosive lithography. At the second stage, PC in the form of square arrays of silicon disk resonators with integrated GeSi CT were formed using plasmochemical etching through a metal mask [11]. The final stage included the removal of the remnants of the chromium metal mask by liquid etching. Two types of PC were formed: 1) PC, in which all disk resonators had the same diameter $D_1 = 900$ nm, 2) PC with a modified crystal structure, which consisted of two square arrays of disks with different diameters ($D_1 = 900$ nm and $D_2 = 870$ nm), inserted into each other (see the box in Figure 1). According to the scanning electron microscopy (SEM) study, the disk resonators had vertical side walls with low roughness, and their height was ≈ 480 nm, which corresponds to the full thickness of the structure under study above the hidden oxide layer. The relative mismatch of the disk diameters $\Delta D = (D_1 - D_2)/D_1$ for PC of the second type was $\sim 3\,\%$. The period of both types of PC was equal to $1\,\mu$m. The luminescent properties of PC structures were studied by the method of micro-photoluminescence (micro-PL). The micro-PL signal was excited by a continuous laser at a wavelength of 532 nm. The laser radiation was focused into a spot $\sim 10\,\mu$m in size using a „Mitutoyo“ M Plan APO NIR 10x (NA = 0.26) lens with a tenfold magnification. The photoexcitation power was 15 mW. The micro-PL spectra were measured with a resolution of $4\,\text{cm}^{-1}$. All measurements were carried out at room temperature. Theoretical calculations of the band diagrams and the emissivity of photonic crystals represented by square arrays of disk resonators were performed using the Fourier modal method in the form of a scattering matrix [12,13]. The refractive indices and extinction coefficients for Si and SiO_2 used in the calculations were selected in accordance with the work data [14,15].

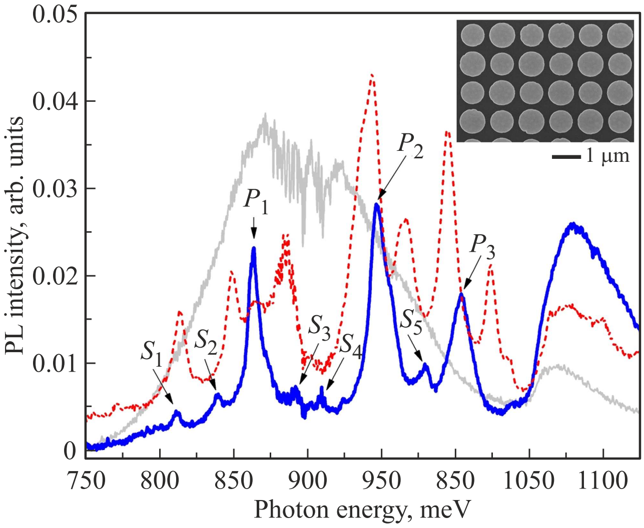

Figure 1. The micro-PL spectra of the test PC with a lattice of disks of the same diameter (blue solid line), PC with a lattice with a base of disks of different diameters (red dotted line) and the spectrum of the initial structure without PC (gray solid line). The spectra were measured at a temperature of 300 K. Laser photoexcitation power was 15 mW. The insert to the figure shows a SEM image (top view) of a photonic crystal with a lattice based on disks of different diameters. The diameters of the disks in the two sublattices forming the PC are $D_1 = 900$ nm and $D_2 = 870$ nm.

3. Results and discussion

Figure 1 shows the spectra of micro-PL PC with the same disk diameters (blue solid line) and PC with a modified structure (red dotted line), as well as the spectrum of the original structure without PC (gray solid line). Two peaks are clearly visible in the micro-PL spectrum of the initial structure: a peak near 1060 meV associated with a signal from silicon, and a wide peak near 800–1000 meV associated with the radiative recombination of charge carriers in GeSi QD [6,7,11]. Three intense peaks (P_1, P_2, and P_3) are observed in the micro-PL spectra of non-modified PC at energies of 864, 947, and 1005 meV, respectively. There are also a number of less intense peaks S_1, S_2, S_3, S_4 and S_5 at 812, 839, 892, 910 and 980 meV, respectively. From the comparison of the spectra, it is clearly seen that a change in the diameters of the disks in the sublattices of the PC leads to a significant increase in the intensity of PL in the vicinity of peaks $S_1 - S_5$, which is accompanied by a change in their spectral position. For example, the intensity of the peaks S_1, S_2 and S_5 increases by almost an order of magnitude, and their spectral position shifts to the region of high photon energies. The detected increase in the intensity of PL peaks in structures with a modified crystal lattice basis can be explained by an increase in the local density of optical states associated with a change in mode dispersions in a structure with a reduced size of the Brillouin zone.

To verify this assumption, theoretical calculations of the band diagrams and the emissivity of photonic crystals with

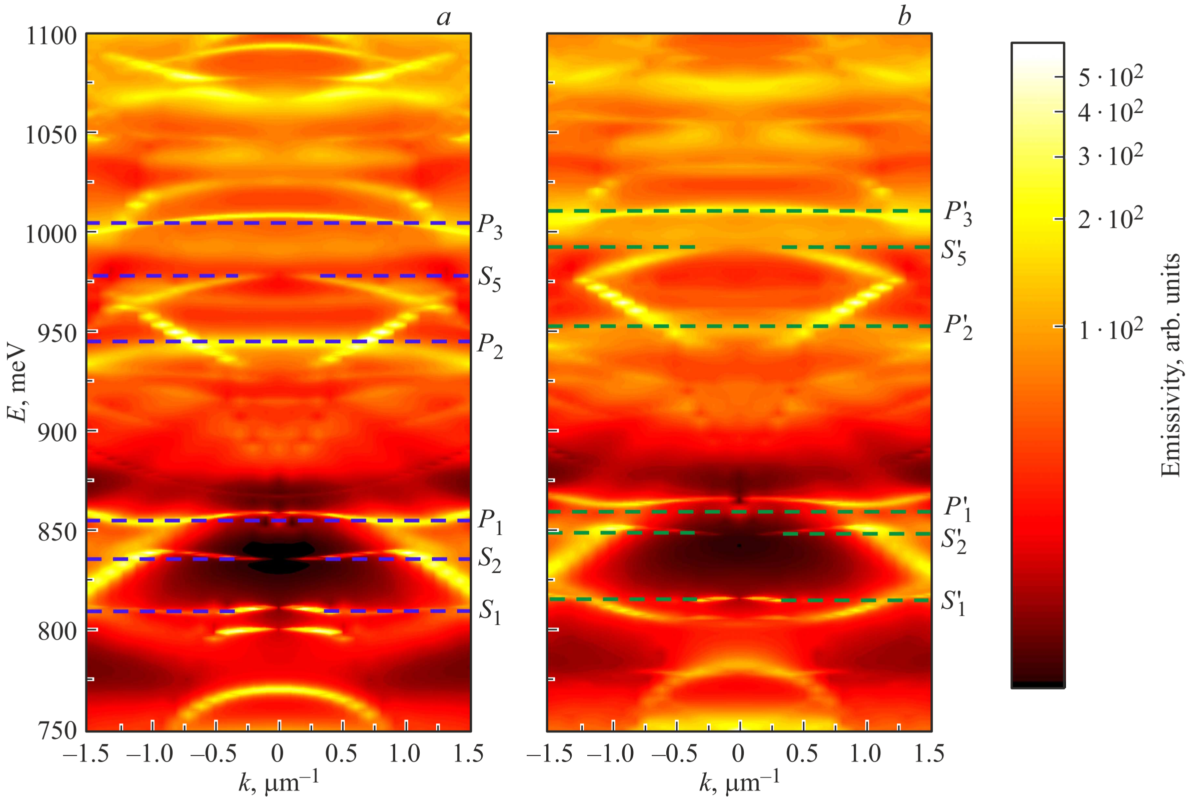

Figure 2. Dispersion dependences of the emissivity of photonic modes excited in PC by radiation from TM-polarized dipoles. Panel (*a*) demonstrates dependencies for PC modes with a lattice of disks of the same diameter, panel (*b*) — for PC with a lattice with a base of disks of different diameters. The dashed lines mark the positions of the experimental peaks of PL. For the BSC modes, a gap in the lines was made in the area of Γ-dot for the convenience of information perception. The refractive indices and extinction coefficients for Si and SiO_2 used in the calculations were selected in accordance with the work data [14,15].

geometric parameters corresponding to the experiment were carried out. The model structure consisted of two square arrays of Si disks inserted into each other, located on a 3 mm thick SiO_2 layer lying on a semi-infinite Si substrate. The active medium from the QD was modeled by radiating dipoles [5], evenly distributed inside Si disks at a depth of 20 to 155 nm, which corresponded to the experimental position of GeSi QD in the studied structure. Figures 2 and 3 show the calculated dispersion dependences of the emissivity of photonic modes excited in PC by radiation from TM and TE polarized dipoles, respectively. The panels (*a*) in the figures demonstrate dependencies for PC modes with a grid of disks of the same diameter. Panels (*b*) — dependencies for PC modules with a grid based on disks of different diameters. The calculated position of the photon modes coincides fairly well with the spectral position of the main radiation peaks observed in the experiment (Figure 1). From the analysis of the obtained dependences, it follows that the experimental peaks $S_1 - S_5$ can be associated with collective modes such as symmetrically protected BSC, since the modes marked in the figure are characterized by the absence of radiation at the Γ-dot ($k = 0$). The peaks P_1, P_2 and P_3 can be attributed to radiating modes, since they do not have this feature at the Γ-dot. It should be noted that the modes S_1, S_2, S_5 are excited by radiation from TM-polarized dipoles (Figure 2, *a*), the modes S_3, S_4 correspond to T-polarization (Figure 3, *a*), and the modes P_1, P_2 and P_3 have no selectivity to the polarization of exciting radiation at all. A comparison of the panels (*a*) and (*b*) in Figures 2, 3 clearly shows that modification of the PC structure by changing the size of disks in one of the sublattices leads to a shift in the spectral position of all modes to the region of higher frequencies. For almost all the modes considered, a weaker dependence on the wave vector is observed in the modified structure (the zones become flatter), which corresponds to an increase in the average local density of optical states over the radiating volume. Figure 4 shows the distribution of electric fields in the near field for the mode S_5 in a PC with a lattice based on disks of different diameters. It is clearly seen that a higher field concentration is observed in disks of smaller diameter, which is a fundamental difference from the field distribution in a PC with a grid of disks of the same diameter, where the field amplitude in all disks is the same. A similar pattern is observed for other modes of the BSC type. This leads to an increase in the characteristic energy of these modes and to a shift of the corresponding peaks to the high frequency range.

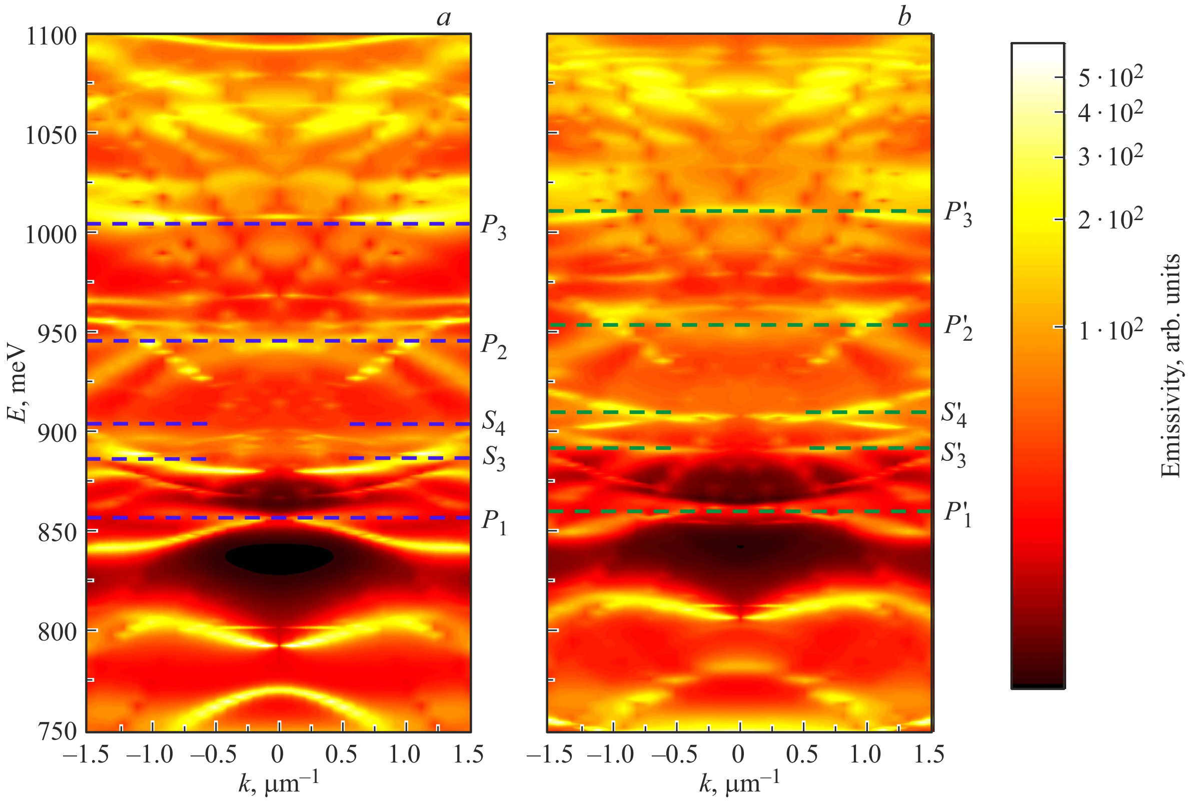

Figure 3. Dispersion dependences of the emissivity of photonic modes excited in PC by radiation from TE-polarized dipoles. Panel (a) demonstrates dependencies for PC modes with a grid of disks of the same diameter, panel (b) — for PC modes with a grid with a base of disks of different diameters. The dashed lines mark the positions of the experimental peaks of PL. For the BSC modes, a gap in the lines was made in the area of Γ-dot for ease of perception of information.

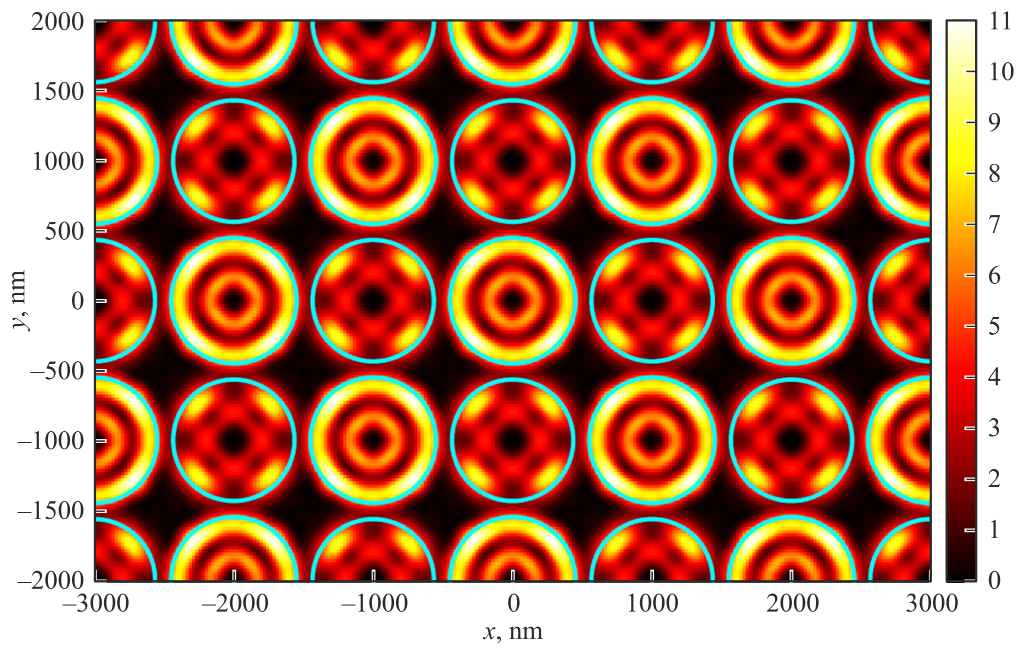

Figure 4. Spatial distribution of the electric field amplitude in the PC plane (in the XY-section drawn at half the height of the disks) for PC with a lattice based on disks of different diameters. The field distribution was calculated at the Γpoint at a photon energy of 997 meV (near the peak of S_5 in the experiment). The diameters of the disks in the two sublattices forming the PC are $D_1 = 900$ nm and $D_2 = 870$ nm. The height of the discs is 480 nm.

4. Conclusion

The results obtained in this work demonstrate that for two-dimensional photonic crystals in the form of subwavelength square arrays of Si disks on SiO_2 with integrated GeSi QDs, modification of the lattice basis of a photonic crystal by changing the diameter of the disks in one of the sublattices can be used to control the spectral position and intensity peaks of radiation coming out of the structure. A comparison of the results of theoretical calculations of the emissivity of the structures under study and the results of measurements using the micro-PL method allows us to conclude that the experimentally observed effect of increasing the intensity of individual PL peaks is probably associated with an increase in the local density of optical states in a lattice with a modified basis.

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Conflict of interest

The authors declare that they have no conflict of interest.

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