Spatial distribution of the luminescence of an electron-hole system in a double-well Si/SiGe/Si heterostructure

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Abstract. The in-plane spatial distribution of photoluminescence (PL) intensity in two-dimensional layers of a type-II (buffer Si1-xGey)/tSi/sSi1-xGey/tSi(cap Si1-xGey) heterostructure is investigated at liquid-helium temperatures at high excitation levels. It is found that the PL spectra recorded at the excitation spot and the edge of the sample are different. This work examines the dependences of the PL spectra and intensity both on the distance between the observation point and a fixed excitation spot and on the distance between the excitation spot and a fixed observation point at the edge of the sample. The reasons for the observed behavior of the PL are determined.

1. Introduction
Interest in the investigation of multiparticle interactions in low-dimensional electron-hole systems of high density has been stimulated by the discovery of new condensed phases with unusual properties in these systems, in particular, an electron-hole liquid (EHL) [1] and a Bose-Einstein condensate (BEC) [2-5]. Theoretical analysis indicated that these phases should exhibit superconductivity and superfluidity [6, 7]. The long-range coherence of the BEC was observed experimentally [8, 9]. These studies were carried out in contravariant (type-I) GaAs/AlGaAs heterostructures with double or wide single quantum wells (QWs) for electrons and holes. The application of an external electric field to these heterostructures leads to the appearance of a spatially indirect energy gap. Then, at low temperatures, a system of nonequilibrium spatially indirect (dipolar) excitons forms under photoexcitation. At high excitation levels, various condensed phases emerge in this system. Photoluminescence (PL) spectroscopy is the main tool for the experimental investigation of the properties of these phases.

In this study, we use PL spectroscopy to study covariant (type-II) Si/SiGe heterostructures, where the electron-hole system should exhibit equally interesting behavior [10-12]. In contrast to GaAs/AlGaAs structures, a spatially indirect electron-hole system can be created in SiGe structures without application of an external electric field. Lifetimes of nonequilibrium charge carriers in silicon, which is an indirect-gap material, are long (more than three orders of magnitude longer than those in GaAs), and this makes it possible to attain high concentrations of charge carriers and investigate their interactions that lead to the formation of multiparticle states even at low excitation levels. The spectra
of multiparticle excited states in the exciton system in a double-QW SiGe/Si heterostructure with a wide range of excitation levels and temperatures were investigated in [13].

This work investigates the spatial distribution of the PL from multiparticle excited states in the electron-hole system in a double-QW SiGe/Si heterostructure.

2. Experimental techniques
A system of dipolar excitons was implemented in a Si_{1-x}Ge_{x}/rSi/sSi_{1-x}Ge_{x}/rSi/Si_{1-x}Ge_{x} (x > y) heterostructure with two QWs for electrons, formed by tensile strained rSi layers separated by a compressively strained sSi_{1-x}Ge_{x} layer acting as a barrier for electrons and a QW for holes. The heterostructure was grown by molecular-beam epitaxy on a single-crystal Si_{0.92}Ge_{0.08} (001) substrate with polished sides. The thickness of the buffer layer of the same composition as the substrate was 100 nm. The thickness of the pseudomorphically grown strained rSi layers was 4 nm. The thickness d of the electron-barrier strained sSiGe layer was 4 nm. A cap layer of the same composition as the substrate completed the design of this structure with two electron QWs. The sample size was 17x7x0.4 mm. The energy-band diagram of the structure is shown in figure 1.

The energy spectrum of the structures under study was investigated by PL spectroscopy in the near-infrared spectral range. The measurements were carried out at a temperature T = 1.8 K and an excitation level P = 100 W·cm⁻². A continuous semiconductor laser with a wavelength λ = 405 nm was used as a PL excitation source. Excitation radiation was incident at an angle of 60 degrees to the structure normal and was focused by a lens into a small spot (P = 100 W·cm⁻²) at the sample surface. Recombination radiation from the sample was collected from the top side of the structure by a lens, analyzed using a grating spectrometer, and detected by a germanium p-i-n photodiode. A lock-in amplifier was used to record the signals. The spatial distribution of the PL was studied in two modes. In the first one, the PL from the edge of the sample was recorded approximately in the direction normal to the structure, and the point of excitation was shifted along the surface by moving the focusing lens perpendicular to the optical axis, thus changing the distance between the edge of the sample and this point (mode A). In the second one, the excitation point was fixed near the center of the structure and the PL observation point was shifted by moving the collecting lens parallel to the structure plane, thus changing the distance between the two points (mode B).

3. Spatial distribution of PL
Figure 2 shows the PL spectrum of the structure from the edge of the sample when the excitation is focused at the center (mode A).
Subst: BE-NP and subst: BE-TO mark the PL lines corresponding to the bound exciton (BE) in the substrate and the buffer and cap layers (no-phonon (NP) and transverse-optical (TO) phonon replicas, respectively). The other PL lines correspond to the Si - SiGe transitions (figure 1). QW: dip EHL-NP and QW: dip EHL-TO correspond to the dipolar EHL lines (NP and TO-phonon replicas, respectively) [13]. The QW: Ex-NP, QW: Ex-TO and QW: Ex-TA lines supposedly correspond to spatially direct excitons (NP and TO phonon and transverse-acoustic (TA) phonon replicas, respectively). This assignment is also supported by the fact that the NP line is more intense than the phonon replicas. This can occur when the electron wave function penetrates into the thin alloy layer. Thus, we assume that both the situations with dipolar and spatially direct carriers are realized in this system. The observation of lines QW: dip EHL-NP and QW: dip EHL-TO and lines subst: BE-NP and subst: BE-TO in the spectra recorded at the edge of the sample is associated with the propagation of recombination radiation within the substrate from the area where the photogenerated carriers recombine (the center of this area coincides with the excitation spot). Their intensities simultaneously oscillate when the excitation point is shifted away from the edge of the sample. Figure 3 shows the oscillations in the intensity of the QW: dip EHL-TO line (circles), measured in mode A.

This behavior is due to the fact that both the dipolar EHL and excitons in the substrate are localized nearly within the excitation region (the localization region is < 0.5 mm). As a result, all these emitters of radiation are almost point-like. Radiation from a point source within the substrate propagates through it like in a planar waveguide and reaches the edge of the sample. This is due to the effect of
total internal reflection. When the emitting region is shifted inside the planar waveguide along its axis, the intensity of radiation emitted from the edge oscillates because radiation escapes through the edge face only if it is incident onto the edge face at an angle smaller than the angle of total internal reflection. This radiation is also totally reflected from the top and bottom faces of the sample. Figure 3 shows that the oscillation period is approximately 1.6 mm. This value is close to the one calculated using the geometric optics considered above.

Almost no oscillations are observed in the intensities of the QW: Ex-NP, QW: Ex-TO and QW: Ex-TA lines. The intensity of the QW: Ex-TO line, measured as a function of distance in mode A, is shown in figure 3 as triangles. Small oscillations are caused by the fact that the QW: Ex-TO line overlaps with the low-energy tail of the oscillating QW: dip EHL-TO line. The absence of oscillations can be explained by the fact that the radiation source is extended. If we assume that these lines are associated with direct transitions, then, due to reemission, there can be a large region of the structure where recombination takes place.

Figure 4 shows intensities of the QW: Ex-TO and QW: EHL-TO lines versus the distance between the excitation and observation points, measured in mode B. One can see that the intensity of the QW: EHL-TO line drops to zero as the distance $x$ increases beyond about 0.5 mm, while the intensity of the QW: Ex-TO line decreases monotonically in the entire range of $x$ investigated. For $x \sim 6.8$ mm, the observation region coincides with the edge of the sample, which leads to an increase in the intensity of the PL lines. Thus, it can be stated that the localization region of the dipolar EHL is approximately 0.5 mm in size, while that of spatially direct excitons corresponds at least to the sample size, that is approximately 1 cm.

4. Conclusion

To summarize, the following results have been obtained.

The spatial distribution of PL along the sample plane in Si$_{1-x}$Ge$_x$/tSi/$\delta$Si$_{1-x}$Ge$_x$/tSi/Si$_{1-x}$Ge$_x$ heterostructures with a 4-nm inner alloy layer has been measured at liquid-helium temperatures and high excitation levels.

It has been found that, when PL is observed from the edge of the sample and the distance between it and the excitation spot is varied, the intensities of some of the PL lines oscillate, while those of other lines do not. The oscillation period is 1.6 mm, which is consistent with model calculations of radiation propagation from a point source in the sample based on geometrical optic considerations that account for the angle of total internal reflection.

It is suggested that the data can be explained by assuming the presence of nonequilibrium carriers of two types: spatially direct and dipolar.
The sizes of the localization areas of the dipolar and spatially direct electron-hole systems have been estimated to be < 0.5 mm and ~ 1 cm, respectively.

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